The Paleocene Hebridean Igneous Province of Scotland

Brian Bell



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Beta version

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Biographical details:

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Front cover The Pulpit Rock, Malcolm's Point, Brolass, SW Mull: A Paleocene flint conglomerate interbedded with basaltic lavas of the Staffa Formation of the Mull Lava Field.

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Forward

The idea for this online publication is based on my collaboration with my good friend and mentor Henry Emeleus, with whom I wrote and illustrated the British Geological Survey's Regional Memoir *The Palaeogene Volcanic Districts of Scotland* (Emeleus & Bell 2005).

The geographic extent of the volcanic and intrusive rocks of the Paleocene Hebridean Igneous Province, which crop out along the west coast of Scotland, mainly between the islands of Skye and Arran, and indeed their age, are necessarily loosely defined. The province covers the northern islands of the Inner Hebrides, with parts of the adjoining Scottish Mainland, plus the Isle of Arran in the Firth of Clyde. This area spans several geological terranes and is characterised by widespread outcrops of igneous rocks, both extrusive and intrusive, of mainly Paleocene age (formerly 'Tertiary') and by locally thick sequences of Mesozoic sedimentary rocks that, in many places, owe their preservation to a protective cover of the Paleocene volcanic rocks. Although this volume concentrates largely upon the geological processes and products of the Paleocene Epoch, it contains relatively detailed accounts of the Pre Mesozoic and Mesozoic rocks.

The first edition of the British Geological Survey's Regional Memoir, which deals with these rocks, was prepared by J E Richey and was published in 1935. It was revised and updated mainly by the original author in the 2nd edition of 1948 and by A G MacGregor and F W Anderson in the 3rd edition of 1961. The completely rewritten and illustrated 4th edition, published in 2005, by Henry Emeleus and myself, provided a more detailed up-to-date account, with the intention that it be comprehensive and of interest to a wide readership.

This online publication is, I hope, a thorough update of the subject matter presented in Emeleus & Bell (2005), in which the level of detail of the text and the number of figures we used was limited by the necessarily modest size of the publication. The present publication includes a considerably larger number of figures (*ca*. 2,000), especially field photographs, and a significantly expanded text. In this publication, certain figures are repeated as they serve multiple purposes within the text. There is no index, as topics of interest can be located by a digital search of the pdf file.

This volume is available free online and it is hoped that those who access it will make a meaningful and generous contribution to the Disaster Emergency Committee (dec.org.uk), or any charity of their choice.

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Figures were prepared by me, other than those acknowledged in the captions.

My sincere thanks to David Bell for providing advice and assistance with layout and formatting.

All errors and omissions are my responsibility. Feedback, positive or negative, is welcomed, and I will endeavour to correct errors. Any images that are supplied will be fully credited.

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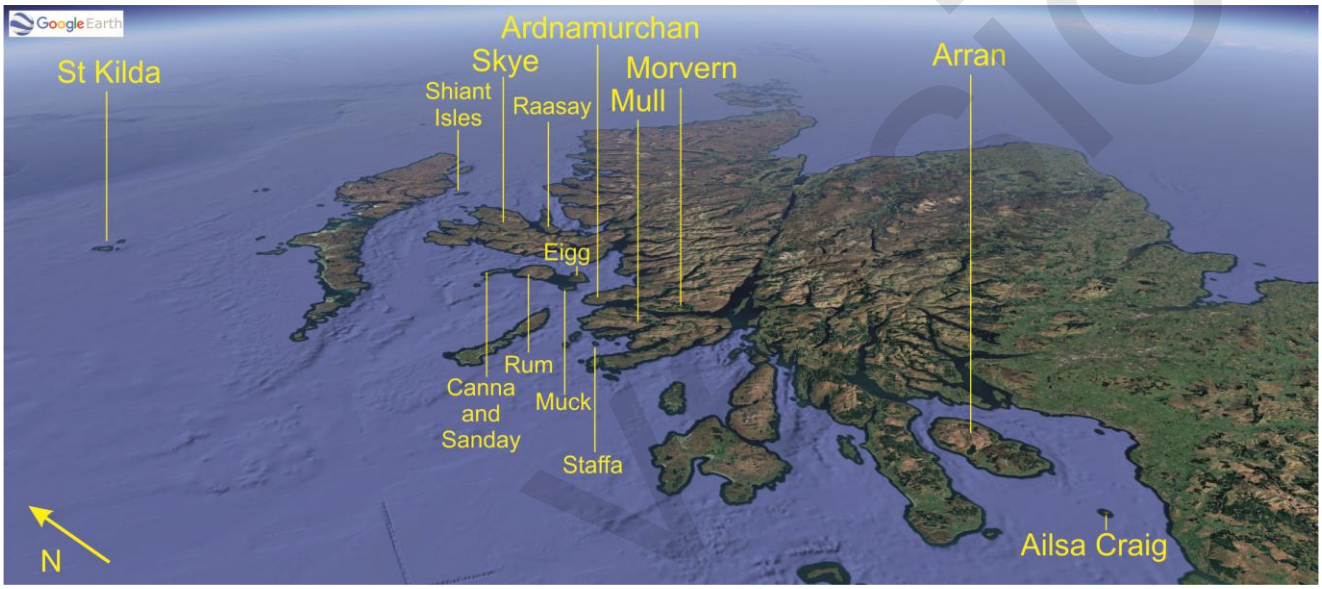


The Old Man of Storr and Needle Rock, Trotternish, Skye

1 Introduction

1.1 Prologue

The magnificent scenery of the Inner Hebridean islands - Skye, Raasay, Rum, Canna, Sanday, Eigg, Muck and Mull - together with Arran and Ailsa Craig in the Firth of Clyde, the St Kilda archipelago, other attendant smaller islands such as the Shiant and the Treshnish isles, and the Scottish Mainland peninsulas of Ardnamurchan and Morvern, are dominated by the Paleocene[1] volcanic and intrusive rocks of the Hebridean Igneous Province (HIP) that record magmatic events that occurred in NW Europe prior to the opening of the NE Atlantic Ocean at *ca*. 55 Ma (Figure 1-1; Figure 1-2; Figure 1-3).



Main locations of the Hebridean Igneous Province (HIP)

The geology of the Hebridean Igneous Province is revealed in countless vistas of majestic mountains and spectacular coastlines. By way of an introduction, a few examples are set out below, in no particular order: Figure 1-4, Figure 1-5, Figure 1-6, Figure 1-7, Figure 1-8, Figure 1-9, Figure 1-10, Figure 1-11; Figure 1-12, Figure 1-13, Figure 1-14, Figure 1-15, Figure 1-16, Figure 1-17, Figure 1-18, Figure 1-19, Figure 1-20, Figure 1-21, Figure 1-22, Figure 1-23, Figure 1-24, Figure 1-25, Figure 1-26, Figure 1-27, Figure 1-28, Figure 1-29, Figure 1-30, Figure 1-31, Figure 1-32, Figure 1-33, Figure 1-34, Figure 1-35, Figure 1-36, Figure 1-37, Figure 1-38, Figure 1-39, Figure 1-40, Figure 1-41, Figure 1-42, Figure 1-43, Figure 1-44, Figure 1-45, Figure 1-46, Figure 1-47, Figure 1-48, Figure 1-49, Figure 1-50, Figure 1-51, Figure 1-52, Figure 1-53, Figure 1-54, Figure 1-55, Figure 1-56, Figure 1-57; Figure 1-58, Figure 1-59, Figure 1-60, Figure 1-61, Figure 1-62, Figure 1-63, Figure 1-64, Figure 1-65, Figure 1-66, Figure 1-67, Figure 1-68, Figure 1-69, Figure 1-70, Figure 1-71 & Figure 1-72.

[1] The use of Pal(a)eocene, as opposed to Palaeogene (see Emeleus & Bell 2005), is a moot point, as only a very few of the volcanic and intrusive units of the Hebridean Igneous Province (see main text) are of Eocene age, albeit very early Eocene (Chapter 5); 56 Ma is a commonly taken date/age for the Paleocene-Eocene boundary.

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Figure 1-1: An Sgùrr, Eigg.



Figure 1-2: The northern Cuillin from Carbost, Skye.

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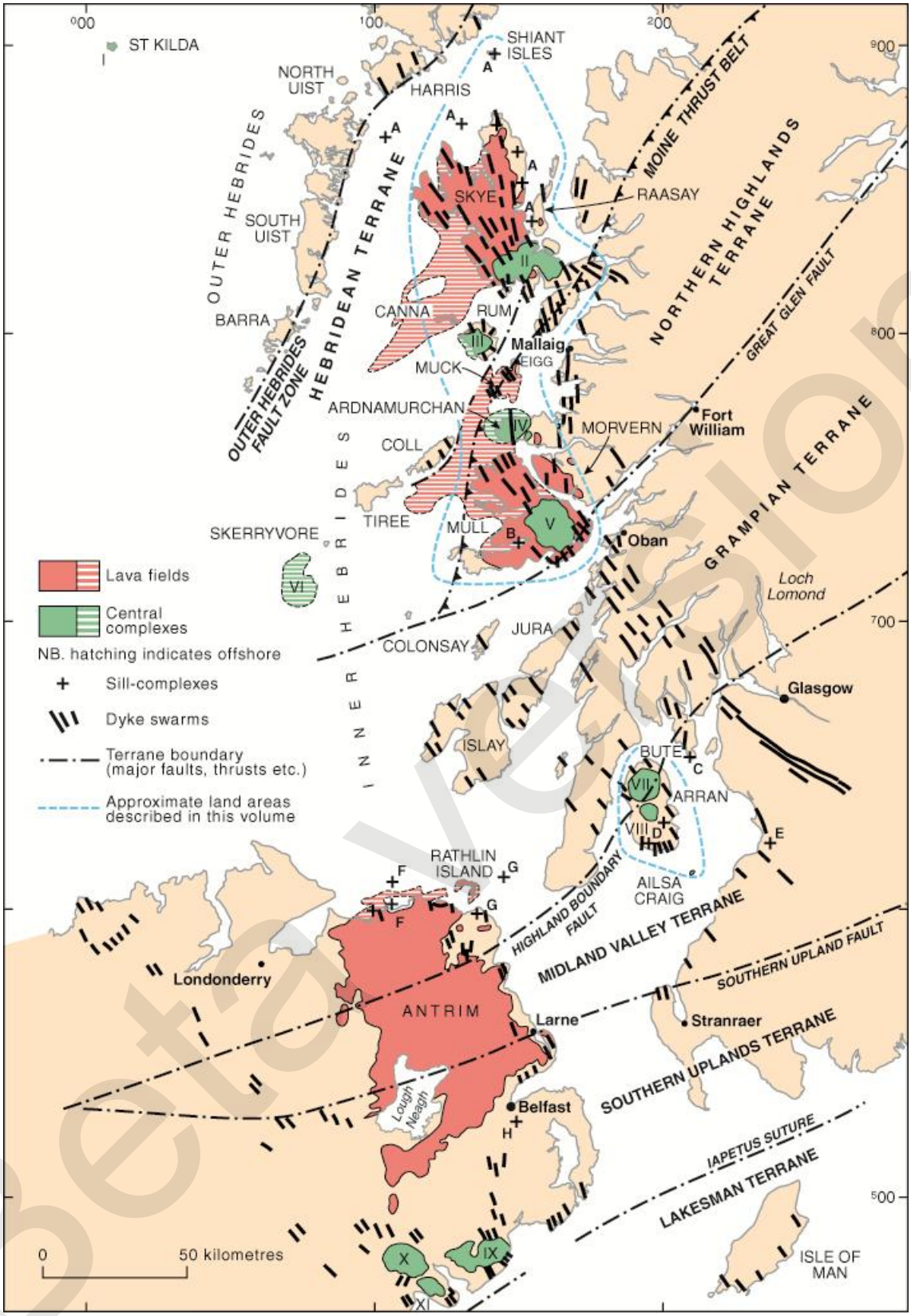


Figure 1-3: Simplified geological map showing the positions of Paleocene central complexes, lava fields, sill-complexes and dyke swarms in western Scotland and NE Ireland (after Emeleus & Bell 2005).

Central complexes: ***I***, St Kilda; ***II,*** Skye; ***III,*** Rum; ***IV,*** Ardnamurchan; ***V,*** Mull; ***VI,*** Blackstones Bank (submerged); ***VII,*** Arran Northern Granite Pluton; ***VIII,*** Arran Central Ring Complex; ***IX,*** Mourne Mountains; ***X,*** Slieve Gullion; ***XI,*** Carlingford.

Sill-complexes: ***A,*** Little Minch; ***B,*** Loch Scridain; ***C,*** Bute; ***D,*** South Arran; ***E,*** Prestwick-Mauchline; ***F,*** Portrush; ***G,*** Fair Head; ***H,*** Scarbo.

Dyke swarms: short, thick bars show trends of the dyke swarms.

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Figure 1-4: Sgùrr nan Gillian, northern Cuillin, Skye.



Figure 1-5: Beinn Dearg Mhòr, Skye.

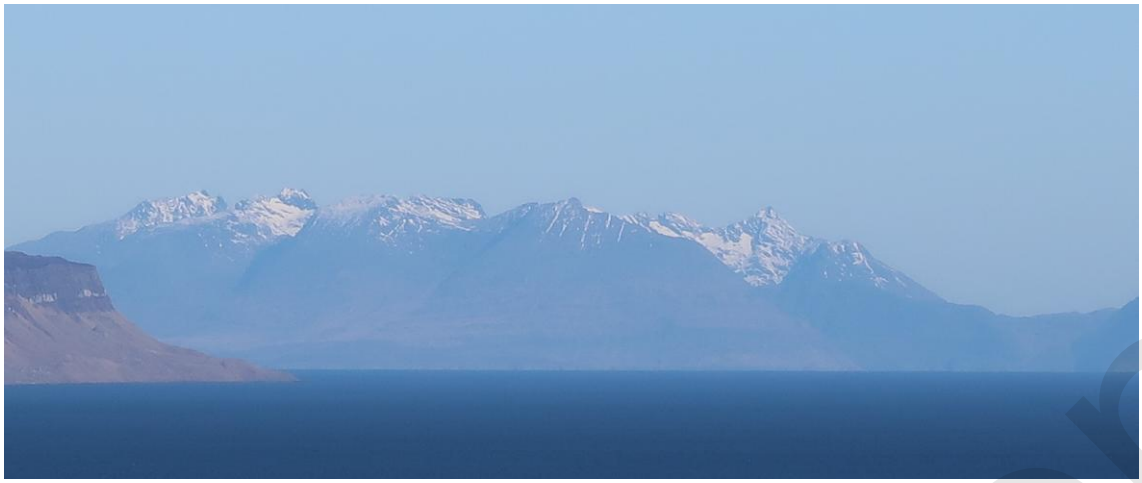


Figure 1-6: The Skye Cuillin from Ardnamurchan.



Figure 1-7: An Carnach, Strathaird, and the Red Hills of Strath, Skye.



Figure 1-8: The Pulpit Rock at Malcolm's Point, Brolass, SW Mull.

Preview version



Figure 1-9: A' Chìoch from Ben More, Mull.



Figure 1-10: Stallachan Dubha, Ben Hiant, Ardnamutchan.



Figure 1-11: Dun Caan and the east coast of Raasay.

Beta version



Figure 1-12: Beinn na h-Urchrach and Ben Hiant, Ardnamurchan.



Figure 1-13: Cir Mhòr and A' Chir from The Saddle, Arran.



Figure 1-14: Bloodstone Hill, NW Rum.

Beta version



Figure 1-15: Dùn Beag, Sanday.



Figure 1-16: Askival, Rum. [Photograph courtesy of David Brown]

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Figure 1-17: Marsco, Glen Sligachan, Skye.



Figure 1-18: The Skye Cuillin from Sanday.



Figure 1-19: Meall Sanna, Ardnamurchan.

Draft version



Figure 1-20: Beinn Iodain, Morvern.



Figure 1-21: Rum from Eilean Carrach, Ardnamurchan.

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Figure 1-22: Southern Cuillin, Skye, from Elgol.

Preliminary Version



Figure 1-23: The Kilt Rock, Skye.



Figure 1-24: NW Hirta, St Kilda.



Figure 1-25: The Quiraing, Skye.

Beta version



Figure 1-26: Eilean an Taighe, Shiant Isles. [Photograph courtesy of Ian Williamson]



Figure 1-27: The Hoe and Moonen Bay, Duirinish, Skye.

Beta version



Figure 1-28: Staffa.



Figure 1-29: Mam Clachaig, Mull. [Photograph courtesy of John Faithfull]

Preview version



Figure 1-30: Rubha Cruinn, Talisker Bay, Skye.



Figure 1-31: The Great Stone Chute, Coire Làgan, Cuillin, Skye.

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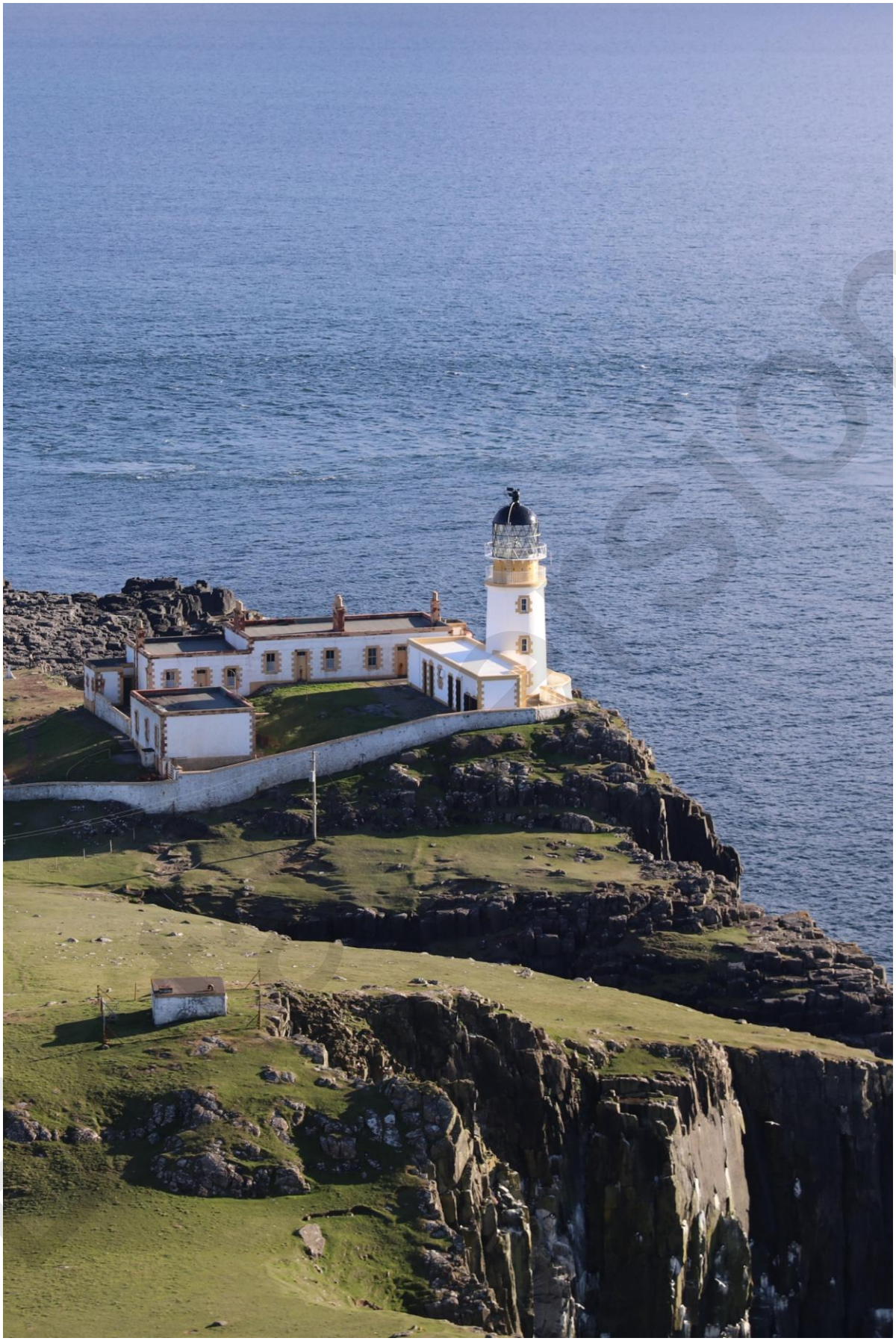


Figure 1-32: Neist Point, Duirinish, Skye.



Figure 1-33: The Red Hills, Kilbride, Strath, Skye.



Figure 1-34: Ben More from Brolass, SW Mull.



Figure 1-35: Dùn Mòr and Dùn Beag, south Sanday.

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Figure 1-36: The Trotternish Escarpment from Loch Sligachan, Skye.

Preview version



Figure 1-37: Coir' a' Ghrunnda, southern Cuillin, Skye, from Soay.



Figure 1-38: The Old Man of Storr, Trotternish, Skye.



Figure 1-39: Cir Mhòr, north Arran.



Figure 1-40: Lorgill Bay, Duirinish, Skye.



Figure 1-41: The Southern Cuillin, Skye.



Figure 1-42: Preshal More and Talisker Bay, Minginish, Skye.



Figure 1-43: Fairy Glen (Glen Uig), Uig, Trotternish, Skye.

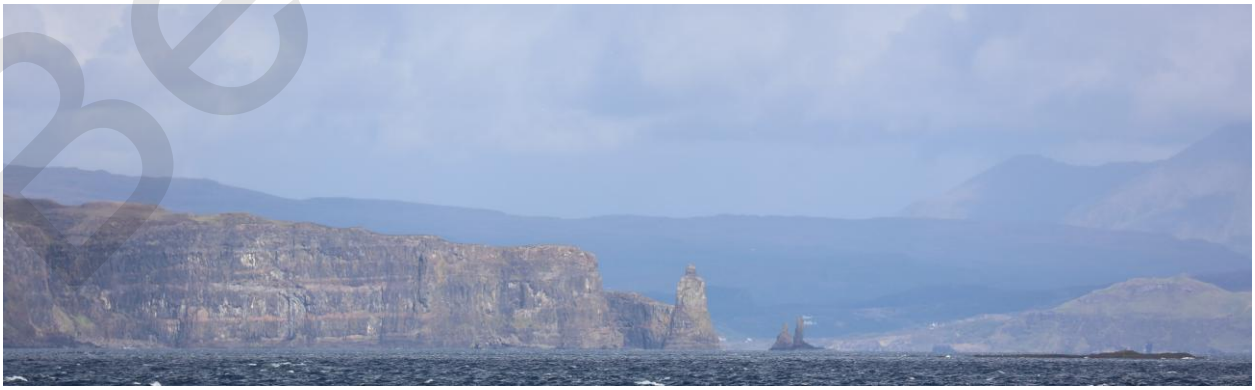


Figure 1-44: Macleod's Maidens, Idrigill Point, Loch Bracadale, Skye.

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Figure 1-45: The Red Hills, Glen Sligachan, and the northern Cuillin, Skye.



Figure 1-46: The Blà Bheinn - Garbh-bheinn ridge, Skye.



Figure 1-47: Boreray, St Kilda.

Preview version



Figure 1-48: Preshal More, Skye.



Figure 1-49: Ruinsival from Harris Bay, with the Bullough Mausoleum in the foreground. [Photograph courtesy of David Brown]



Figure 1-50: Ardnamurchan Point from Eigg.

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Figure 1-51: The Old Man of Storr and The Storr from off the east coast of Trotternish, Skye.



Figure 1-52: Lochs Cuilce (near) and Coruisk (far) on the south side of the Cuillin, with the Skye Red Hills in the distance.



Figure 1-53: West coast of Strathaird and Blà Bheinn, Skye.



Figure 1-54: Sgùrr an Fheadain and (beyond) Bidein Druim nan Ramh, northern Cuillin, Skye.



Figure 1-55: Ailsa Craig from the south coast of Arran.

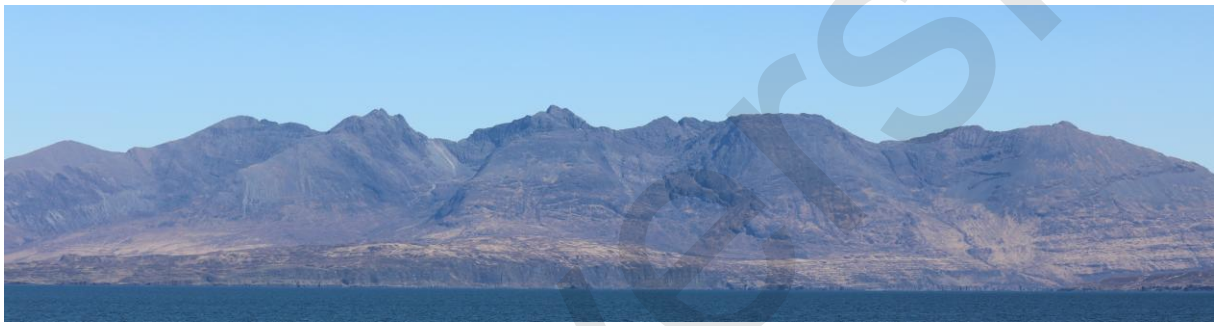


Figure 1-56: The Skye Cuillin from Sanday.



Figure 1-57: Healabhal Bheag (Macleod's Table South), Duirinish, Skye.

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Figure 1-58: The ridge of An Sgùrr, south Eigg, from the Sound of Eigg.



Figure 1-59: East Eigg (near) and the Rum Cuillin (far).



Figure 1-60: Sleat, SE Skye (near) and the ridge of the Skye Cuillin (far).

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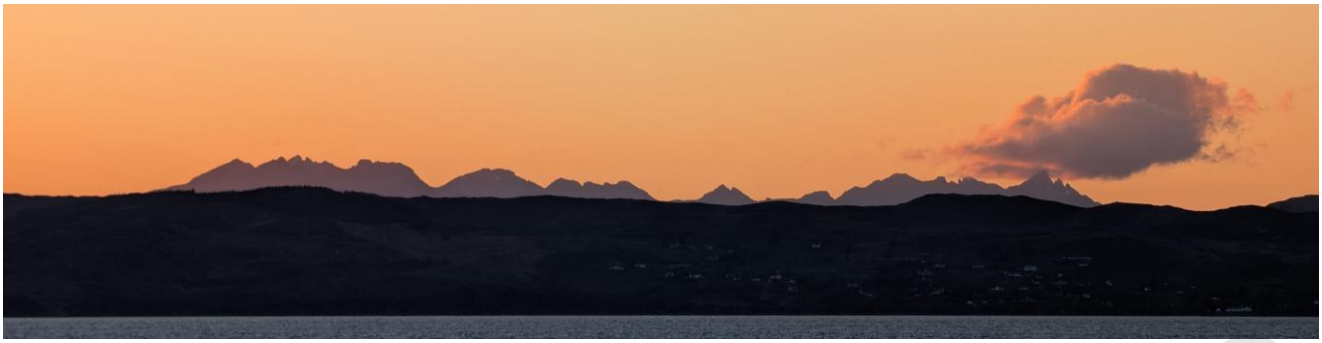


Figure 1-61: Evening silhouette of the Skye Cuillin from Mallaig.



Figure 1-62: Evening silhouette of the Rum Cuillin from Mallaig.



Figure 1-63: Blà Bheinn and the village of Elgol, Strathaird, Skye.

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Figure 1-64: Askival (left) and Hallival (right) of the Rum Cuillin from Eigg.



Figure 1-65: Sanday (left) and Canna (right) from the Sound of Canna.



Figure 1-66: South side of Ailsa Craig, illustrating the vertical columnar joints throughout much of the outcrop. Summit 340 m OD.

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Figure 1-67: Compass Hill, Canna.



Figure 1-68: Skye Cuillin from Sanday.



Figure 1-69: Canna Harbour, Sanday and NW Rum.

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Figure 1-70: Bay of Laig and An Sgùrr, Eigg.



Figure 1-71: The Storr, Trotternish, Skye.

Preview

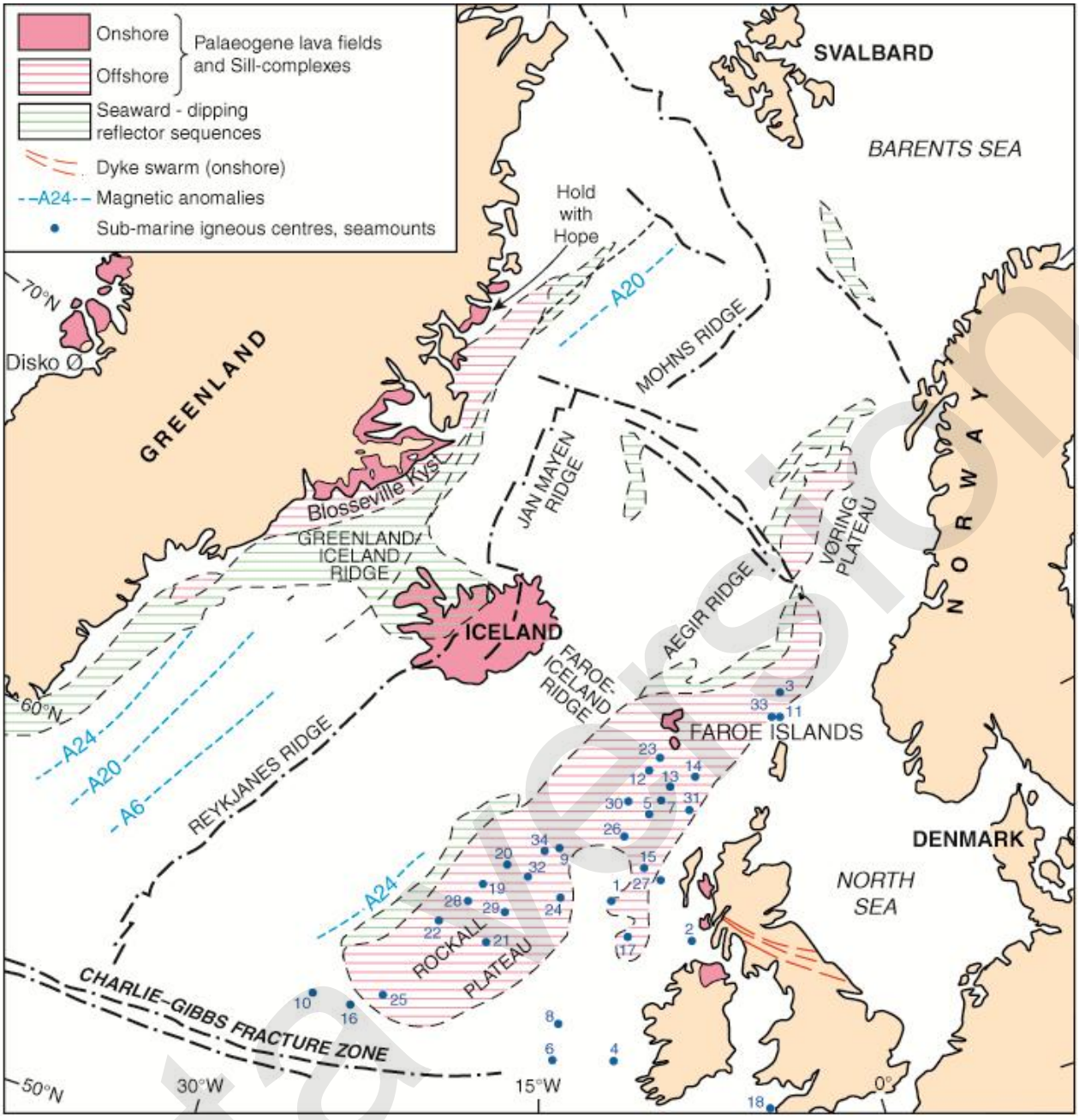


Figure 1-72: The NW end of Loch Coruisk, Skye Cuillin.

The variety of igneous rocks forming the dramatic coastal cliffs and glacially sculpted mountains of the Inner Hebrides provide a detailed record of Paleocene volcanism and shallow magma emplacement events that tell of the birth and death of fissure and related central volcanoes. These central volcanoes have been laid bare by weathering and erosion since the Early Eocene, most dramatically by the myriad of glacial events of the last 2.5 million years during the Quaternary Period. The central complexes are essentially the roots of these volcanoes, each different in their construction.

These Paleocene igneous rocks are part of a larger geological entity, the North Atlantic Igneous Superprovince (NAIS), which extends to the Faroe Islands, East and West Greenland and Baffin Island (Figure 1-73; Figure 1-74; Figure 1-75; Figure 1-76; Figure 1-77; Figure 1-78; Figure 1-79). The NAIS developed prior to the initiation of ocean floor spreading in the NE Atlantic at *ca*. 55 Ma, today most graphically illustrated by the volcanic rocks of Iceland, where additional input to the magmatic activity is provided by a plume, which brings magma from a deeper part of the Earth's Mantle.

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1 Anton Dohrn
2 Blackstones
3 Brendan (Shetland)
4 Brendan (Ireland)
5 Darwin
6 Donn
7 Drekaegya
8 Drol
9 East George Bligh
10 Eriador
11 Erlend
12 Faroe Bank
13 Faroe Bank Channel Knoll
14 Fraenir
15 Geikie
16 Gondor
17 Hebrides Terrace
18 Lundy
19 Lyonesse
20 Mammal
21 Mentone
22 Owlsgard
23 Regin Smidur
24 Rockall
25 Rohan
26 Rosemary Bank
27 St Kilda
28 Sandarro
29 Sandastre
30 Sigmundur
31 Sula Sgeir
32 Swithin
33 West Erlend
34 West George Bligh

Figure 1-73: The North Atlantic Igneous Superprovince (NAIP), showing the extent of onshore and offshore igneous activity (after Emeleus & Bell 2005).

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Figure 1-74: Sheet lavas, Kunoy, Faroe Islands.



Figure 1-75: Sheet lavas, Stidjafjall Tungulidfjall, Nordradalur, Streymoy, Faroe Islands.

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Figure 1-76: Skaergaard Central Complex, East Greenland.



Figure 1-77: Sheet lavas, Södalen, East Greenland.

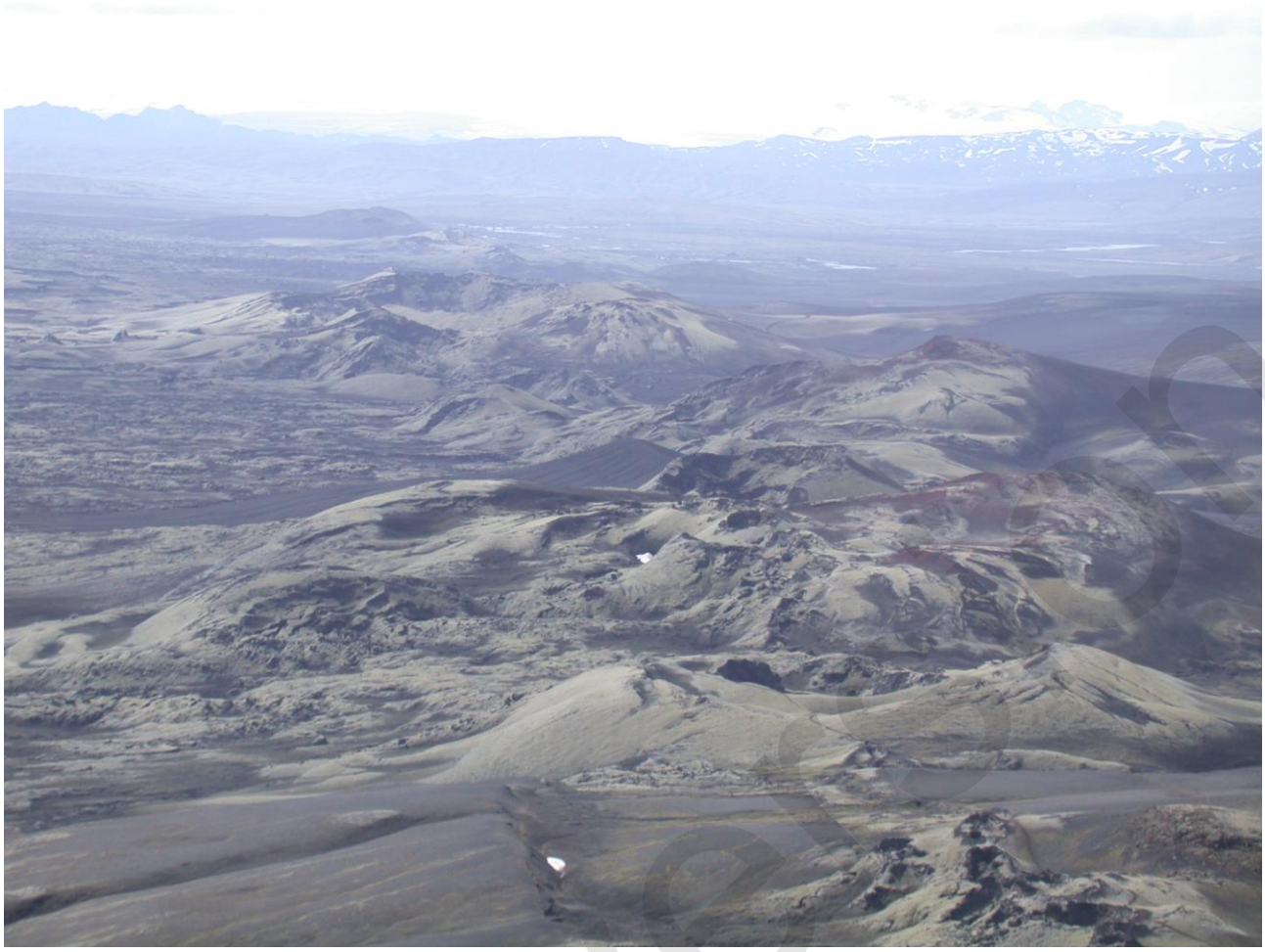


Figure 1-78: Laki fissure system, Iceland.



Figure 1-79: Öskjuvatn, Askja caldera, Iceland.

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This account focuses on the Scottish part of the NAIS, referred to as the Hebrides Igneous Province (HIP), although it extends south into Northern England in the form of a dyke swarm associated with the Mull lava field and central complex. In the opposing direction, this dyke swarm extends NW into the Outer Hebrides. The volcanic sequence of Antrim and the Mourne, Carlingford and Slieve Gullion central complexes are not dealt with here.

In addition, the basement Archaean Lewisian Gneiss Complex and Late Proterozoic (or Neoproterozoic) and Phanerozoic sedimentary and volcanic rocks that underlie the volcanic sequences and act as country-rocks to the intrusive rocks record much of the varied geological history of NW Scotland, from lower crustal processes, Palaeozoic (Period) mountain building events, and the development of fault-controlled Mesozoic sedimentary basins.

1.2 Geological summary

The HIP, extending from Arran in the south to Skye and St Kilda in the north, crosses several tectonic crustal terranes, all located on the margin of the supercontinent of Laurentia prior to the Caledonian Orogeny. The basement Archaean Lewisian Gneiss Complex (Figure 1-80; Figure 1-81; Figure 1-82) records multiple deformation and metamorphic events, many of which have been identified and quantified by detailed isotopic studies. These gneisses underpin the Hebridean (tectonic) Terrane, which forms the foreland of the Caledonian Mountain Belt, NW of the Moine Thrust Zone (MTZ), and, most likely, the younger rocks of the Northern Highlands Terrane (Figure 1-83). These basement rocks also crop out in Greenland and parts of North America.



Figure 1-80: Lewisian Gneiss Complex, south Loch Arnish, north Raasay.

Pre-publication version



Figure 1-81:Detail of banded gneiss of the Lewisian Gneiss Complex, south Loch Arnish, north Raasay. Pole *ca*. 1 m long.



Figure 1-82: Folded, banded mafic (dark) and granitic (pale) gneiss of the Lewisian Gneiss Complex, south of Beinn na h-Iolaire, north Raasay. Pole *ca*. 1 m long.

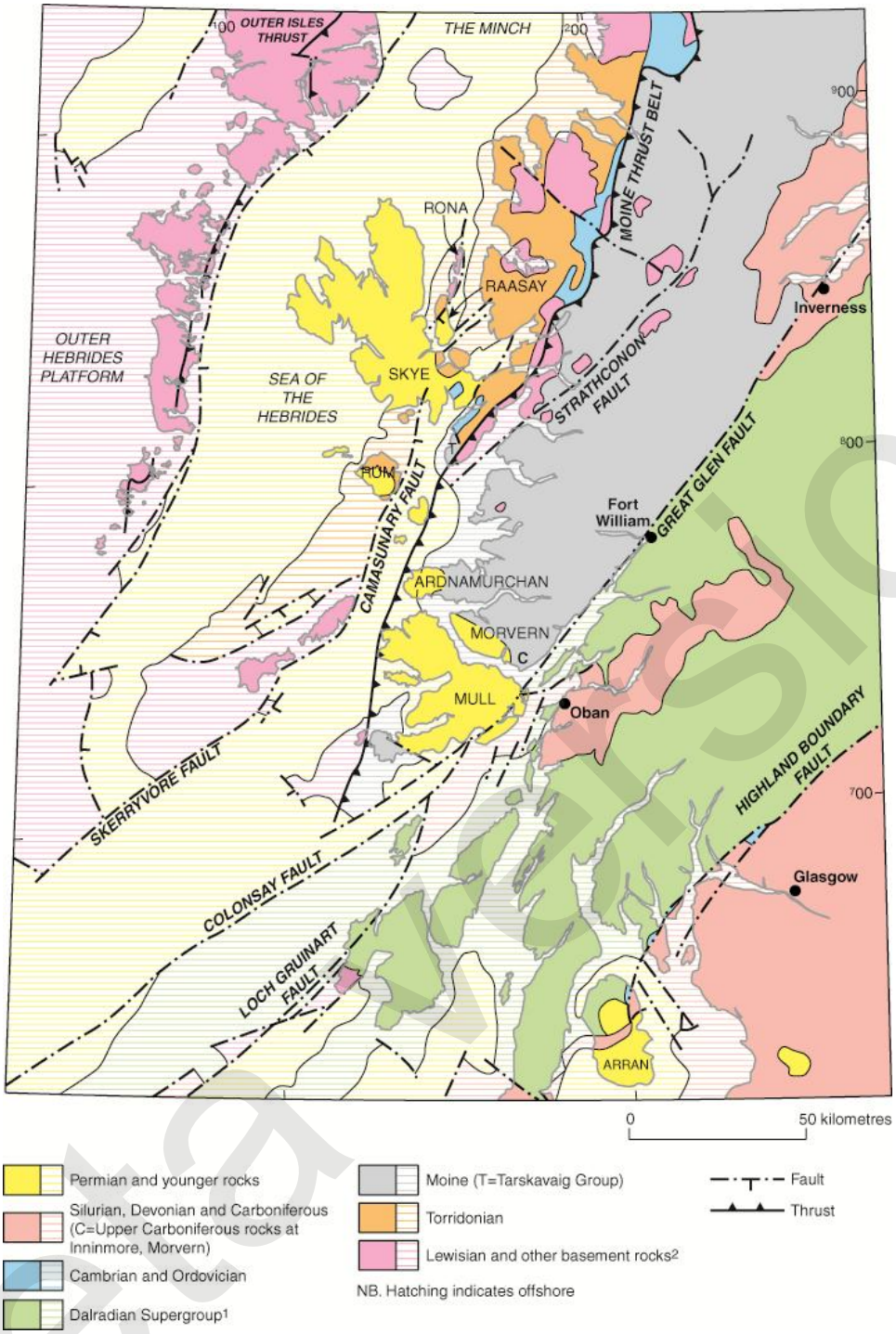


Figure 1-83: Onshore and offshore distribution of Precambrian and Lower Palaeozoic rocks along the western seaboard of Scotland [1, includes the Bowmore and Colonsay groups on and offshore Islay; 2, includes gneisses of the Rhinns Complex south of the Great Glen Fault] (after Emeleus & Bell 2005).

Within the Hebridean Terrane, the Lewisian Gneiss Complex constitutes the crystalline basement and is unconformably overlain by a thick sequence of Late (or Meso- to Neo-) Proterozoic continental margin strata, the Torridonian Supergroup, commonly referred to as the 'Torridonian' (Figure 1-84; Figure 1-85; Figure 1-86), in turn unconformably overlain by coastal and marine clastic and carbonate Cambro-Ordovician strata.

The alluvial fan, fluvial and lacustrine strata of the Torridonian Supergroup were sourced from a hinterland to the NW of the Outer Hebrides and deposited predominantly within an alluvial fan, braided river and lake

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system. The sediment source was basement gneisses of the Laurentian Shield, within the age range *ca*. 2500 Ma to *ca*. 1100 Ma.



Figure 1-84: Cross-stratified Torridon Group arkosic sandstones, Leac-stearnan Member, Applecross Formation, Torridon Group, An Dubh-sgeire, east Soay.



Figure 1-85: Distorted laminae within sandstones and siltstones of the Loch an Uach(-dair) Member, Diabaig Formation, Torridon Group, immediately NW of Loch Beag, north Raasay. Pole *ca*. 1 m long.

Proof version



Figure 1-86: Tabular fine-grained sandstones, siltstones and shales with well-developed ripples in the Sgùrr na Stri Member, Diabaig Formation, Torridon Group, in the coastal section on the west side of Camas Fhionnairigh (Camasunary), south Skye. Pole *ca*. 1 m long.

The eastern boundary of the Hebridean Terrane is the Moine Thrust Zone, which constitutes the NW margin of the Caledonian Orogenic Belt. Within this thrust zone, from Durness in the Northern Highlands to Skye and Rum in the south, all of the foreland lithologies, together with thrust-bounded sections of Moine Supergroup strata, form thrust sheets, or nappes.

East of the Moine Thrust Zone is the Northern Highlands Terrane, which comprises a single lithological unit, the Moine Supergroup, mainly psammites and pelites (Figure 1-87; Figure 1-88; Figure 1-89). The Late (or Neo-) Proterozoic Moine Supergroup is interpreted to be (in part) laterally equivalent to the Torridonian Supergroup (separated by westerly transporting thrusts of the Moine Thrust Zone). The Moine Supergroup rocks were deformed and metamorphosed during the Knoydartian Orogeny at *ca*. 800 Ma and later affected by events of the Caledonian Orogeny. In SE Skye, the Tarskavaig Group, a sequence of low-grade metamorphosed psammitic rocks, may provide a link between Torridonian Supergroup strata and Moine Supergroup strata. Rocks of the Moine Supergroup also occur around and within the Ardnamurchan and Mull central complexes.



Figure 1-87: Folded psammites, pelites and amphibolites of the Assapol Group of the Moine Supergroup, at Àird Dubh on the east side of Ardalanish Bay, SW Mull.

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Figure 1-88: Detail of the folded psammites, pelites and amphibolites of the Assapol Group of the Moine Supergroup, at Àird Dubh on the east side of Ardalanish Bay, SW Mull.



Figure 1-89: Folds within a sequence of interbedded psammites and pelites, illustrating the relationship between fold size and bed thickness, with larger open folds in thicker beds and smaller more complex folds in thinner beds. Àird Dubh on the east side of Ardalanish Bay, SW Mull.

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The final lithostratigraphic unit of the Hebrides Terrane foreland comprises coastal plain to marine Cambro-Ordovician clastic sequences, predominantly quartz sandstones ('quartzites') and shales, overlain by fully marine strata, mainly dolostones (Figure 1-90; Figure 1-91).



Figure 1-90: Deformed pure quartz sandstones ('quartzite') of the False-bedded Quartzite Member of the Eriboll Sandstone Formation, Sgiath-bheinn an Uird, Sleat, SE Skye.



Figure 1-91: Limestone (dolostone) pavement with clints and grykes, Strath Suardal Formation, Durness Group, NW Bheinn Shuardail (Suardal), Strath, Skye.

To the SE of the Great Glen Fault, the Grampian Terrane is dominated by rocks belonging to the Dalradian Supergroup, which crop out in SE Mull and northern Arran (Figure 1-92; Figure 1-93). They include a variety of meta-sedimentary and meta-igneous rocks, mainly of Late Proterozoic age, although the youngest may

be of earliest Cambrian age. In eastern Arran, black mudstones, cherts and pillow lavas of Ordovician age belong to the Highland Border Complex (Figure 1-94).



Figure 1-92: Folded phyllites of the Dalradian Supergroup, Imachar, NW Arran. Pole *ca.* 1 m long.



Figure 1-93: Thin laminated phyllites of the Dalradian Supergroup, Imachar, NW Arran. Pole *ca.* 1 m long.



Figure 1-94: Ordovician pillow basaltic lavas within the Highland Border Complex, North Glen Sannox, NE Arran. Pole *ca*. 1 m long. [Photograph courtesy of Ian Williamson]

The Torridonian, Moine and Dalradian sequences were deposited in extensional basins on what was to become a passive margin of Laurentia. The Cambro-Ordovician rocks of the NW Highlands were subsequently deposited on this passive margin, while the rocks of Highland Border Complex were formed within the adjacent expanding ocean. In Late Proterozoic to Early Palaeozoic time, this Iapetus Ocean separated Laurentia from the supercontinent of Gondwana(land), which included the basement of present-day England, Wales, southern Ireland and western Europe, and the continent of Baltica (present-day Scandinavia and Russia). The complex sequence of plate tectonic events that led to the closure of this ocean, culminated in the collision and fusion of the bounding continents to form the new supercontinent of Laurussia, resulting in the Caledonian Orogeny. Closure of the Iapetus Ocean most likely commenced in the Early Ordovician and was completed by the end of Silurian time, although post-collision uplift, with associated magmatism, continued throughout most of the Early Devonian.

The effects of the Caledonian Orogeny are predominantly recorded in the Northern Highlands and Grampian terranes, with the culmination of deformation and metamorphism referred to as the Grampian Event(s). These events occurred during the Early to Mid-Ordovician and were accompanied by the intrusion of large volumes of Mantle-derived basic magma and by crustal melting to produce a suite of granitic plutons. It is likely that the Highland Border Complex was obducted onto the continental margin during these compressional events.

Subsequently, in Mid Silurian time, large-scale thrust events resulted in significant crustal shortening, with the NW portion of the Caledonian orogenic belt/front transported over the foreland Hebridean Terrane along the Moine Thrust Zone. Concurrently, there were major movements on the Outer Hebrides Fault zone. This Mid Silurian deformation event, commonly referred to as the Scandian Orogeny, was

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associated with the emplacement of highly alkaline magmas within and around the Moine Thrust Zone. Elsewhere, during subsequent uplift events, calc-alkaline granitic plutons continued to be emplaced into the Northern Highlands and Grampian terranes, overlapping with calc-alkaline volcanism in Late Silurian to Early Devonian times. By then, subduction beneath the Laurentian margin had ceased following continent–continent collision, with all of the Silurian and Devonian magmatism having subduction-related characteristics. Widespread Caledonian intrusions are represented in HIP by the Ross of Mull Pluton in SW Mull and by a variety of minor intrusions (Figure 1-95; Figure 1-96). The crustal terranes were juxtaposed, into their present positions, by large sinistral (left-lateral) movements on bounding faults, such as the Great Glen Fault, during the later stages of the Scandian Orogeny. Major lateral movements on other NE-SW-trending faults most likely occurred at the same time.



Figure 1-95: The Early Devonian Ross of Mull Granite Pluton, with abundant dark inclusions (enclaves) of co-genetic diorite. East side of Erraid Sound, Ross of Mull, SW Mull.



Figure 1-96: Pale apophyses of the Ross of Mull Granite Pluton within dark, thermally metamorphosed pelites of the Moine Supergroup sequence, west side of Ardalanish Bay, Ross of Mull, SW Mull. Pole *ca*. 1 m long. [Photograph courtesy of Ian Williamson]

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Minor outcrops of Late Silurian to Early Devonian sedimentary and volcanic rocks occur in eastern Mull. On Arran, the country-rocks around the Paleocene intrusions include Lower and Upper Old Red Sandstone conglomerates and sandstones of Late Silurian to Early Carboniferous age, deposited by alluvial fans and rivers draining from the north and NE. These so-called Old Red Sandstone deposits (Figure 1-97), together with Lower Carboniferous sandstones, siltstones, limestones and basaltic lavas on Arran (Figure 1-98), form part of the Midland Valley Terrane. Elsewhere, Carboniferous rocks are not common but include an inlier of Upper Carboniferous rocks on Arran and on Morvern. A few dykes of Late Carboniferous to Early Permian age cross the region, and quartz-dolerite plugs, for example in Morvern, may also date from this time.



Figure 1-97: Hutton's Unconformity, with inclined (top right to bottom left) Lower Devonian (Old Red Sandstone) sandstones overlying near-vertical Dalradian Supergroup phyllites (bottom right), Newton, north Arran. Pole *ca*. 1 m long.



Figure 1-98: Inclined Carboniferous (Namurian) sandstones and siltstones between Laggan and Cock of Arran, north Arran. Pole *ca*. 1 m long.

Large sedimentary basins were initiated towards the end of the Palaeozoic Era and continued to develop during the Mesozoic and Cainozoic eras. These basins, or troughs, trend approximately N-S and include the Sea of the Hebrides - Little Minch Trough, the Inner Hebrides Trough and the Blackstones and Colonsay basins. During the Permian and Triassic periods, thick sedimentary sequences accumulated in these troughs, consisting of both desert and fluviatile sandstones (Figure 1-99; Figure 1-100; Figure 1-101).



Figure 1-99: Permian sandstones and conglomerates, SE of the Cock of Arran, north Arran. Pole *ca*. 1 m long.



Figure 1-100: Dune-bedded Permian sandstones, south of harbour, Corrie, NE Arran. Pole *ca*. 1 m long.



Figure 1-101: Triassic conglomerates, Rubhan na Leac, SE Raasay. Pole *ca*. 1 m long.

The Jurassic Period was characterised by shallow water sedimentation and, up-sequence, shows a progressive change from brackish water to fully marine conditions (Figure 1-102; Figure 1-103; Figure 1-104 Figure 1-105). The basin margin deposits occur onshore at several locations within the Inner Hebrides and were faulted, tilted and folded after Late Jurassic (Kimmeridgian) time, prior to the deposition of Upper Cretaceous (Cenomanian to Middle Turonian) marine sandstones and limestones (chalk). These Cretaceous rocks occur widely throughout the Inner Hebrides but are typically very thin and laterally variable.



Figure 1-102: Shallow marine Lower Jurassic sandstones and shales unconformably overlying pale Cambro-Ordovician Durness Group dolostones; the cliffs in the distance comprise strata of the marine Lower Jurassic Pabay Shale Formation. East side of Loch Slapin, Strath, Skye.

Preview version



Figure 1-103: Shallow marine Middle Jurassic Druim an Fhurain Sandstone Member of the Bearreraig Sandstone Formation, Great Estuarine Group, Druim an Aonaich, south of Screapadal, east Raasay. Cliffs *ca*. 250 m high. Summit in distance is Dùn Caan.



Figure 1-104: Pale, inclined Elgol Sandstone Formation, Great Estuarine Group, Elgol, Strathaird, Skye.

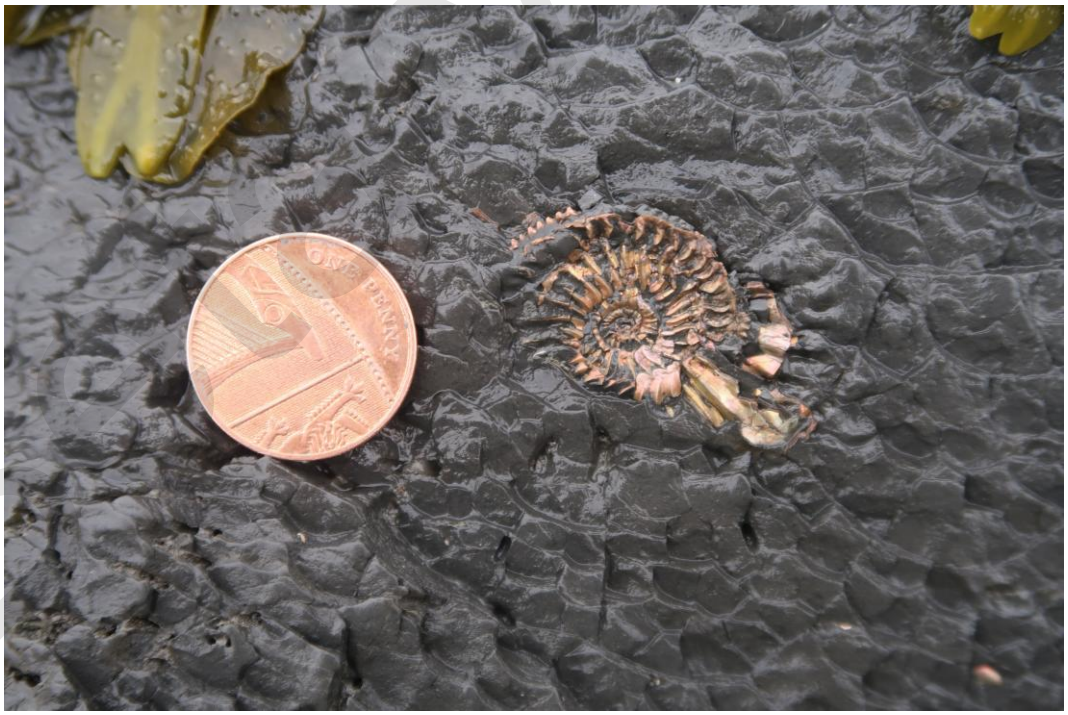


Figure 1-105: Mineralised fragment of an ammonite in shales of the marine Upper Jurassic Staffin Shale Formation, Flodigarry, Trotternish, north Skye. Coin *ca*. 20 mm across.

Review version

Uplift and ensuing erosion between the end of the Turonian and the earliest Paleocene produced a land surface on which the first volcaniclastic rocks and basaltic lavas of the Hebridean Igneous Province were deposited. Conspicuous coarse clastic sedimentary rocks intercalated within the lower parts of the Inner Hebrides lava sequences suggest that this land surface may have had significant relief, albeit locally. Shallow lakes, ponds and rivers covered the land surface and the basal beds of the Paleocene sequences are generally water-laid tuffaceous sandstones and siltstones, commonly with plant remains, and less common hyaloclastite deposits (Figure 1-106). These clastic rocks are overlain by thick, predominantly basaltic, subaerial lava successions of which the earliest are those of Muck, Eigg and the basal members of the Mull succession (Figure 1-107; Figure 1-108; Figure 1-109). The eruption sites of the lavas were isolated vents that developed along fissure systems now represented by NW-SE -trending dyke swarms.



Figure 1-106: Hyaloclastite beds, Skye Lava Field, Craig Ulatota, Trotternish, Skye. Pole *ca.* 1 m long.



Figure 1-107: Volcanic sequence of the Mull Lava Field, Malcolm's Point, Brolass, SW Mull. Height of cliff *ca.* 300 m.

Beta Version



Figure 1-108: Paleocene basaltic lavas intruded by thin dolerite dykes forming The Storr on the east side of Trotternish, north Skye.



Figure 1-109: Macculloch's Tree Lava, Ardmeanach, west Mull. Vertical fossil tree is at back of pale peeble beach.

Several well-defined NW-SE -trending regional dyke swarms cross the HIP and beyond, best developed and most intense in the vicinity of the central (intrusive) complexes. These swarms reflect a regional NE to SW extensional stress system and many of the dykes most likely fed lava flows.

In addition, sills of ultrabasic to basic composition occur widely, with extensive sill-complexes intruded into the Mesozoic basin deposits, for example the Little Minch Sill-complex which crops out in north Skye and offshore islands such as the Shiant Islands in the North Minch (Figure 1-110; Figure 1-111).



Figure 1-110: Layered picrite sill forming the headland at Duntulm in NW Trotternish, north Skye.



Figure 1-111: Olivine dolerite sill of the Little Minch Sill-complex forming Neist Point, Duirinish, Skye.

Beta version

The central complexes are the deeply eroded roots of major volcanoes. With a few exceptions, they postdate the preserved lava fields and overlapped in time with the intrusion of the related dyke swarms. The central complexes represent a fundamental change in the character of the igneous activity, from the widespread fissure feeders of the lava fields to much more localised or centralised and intense magmatism of shield volcanoes. There was a marked change, too, in the composition of the magmas. This is evident when the predominantly basaltic lava fields are compared and contrasted with the compositionally diverse intrusions of the central complexes, which include peridotite, olivine gabbro, granitic rocks and minor amounts of rock of intermediate composition (Figure 1-112; Figure 1-113; Figure 1-114). Within the central complexes, granites generally form a significant proportion of the surface outcrop, although surveys of the gravity and magnetic fields over the central complexes indicate that each has a substantial core of dense basic and/or ultrabasic rocks and that, despite their considerable areal extent, the granitic rocks are relatively thin and 'superficial' bodies.

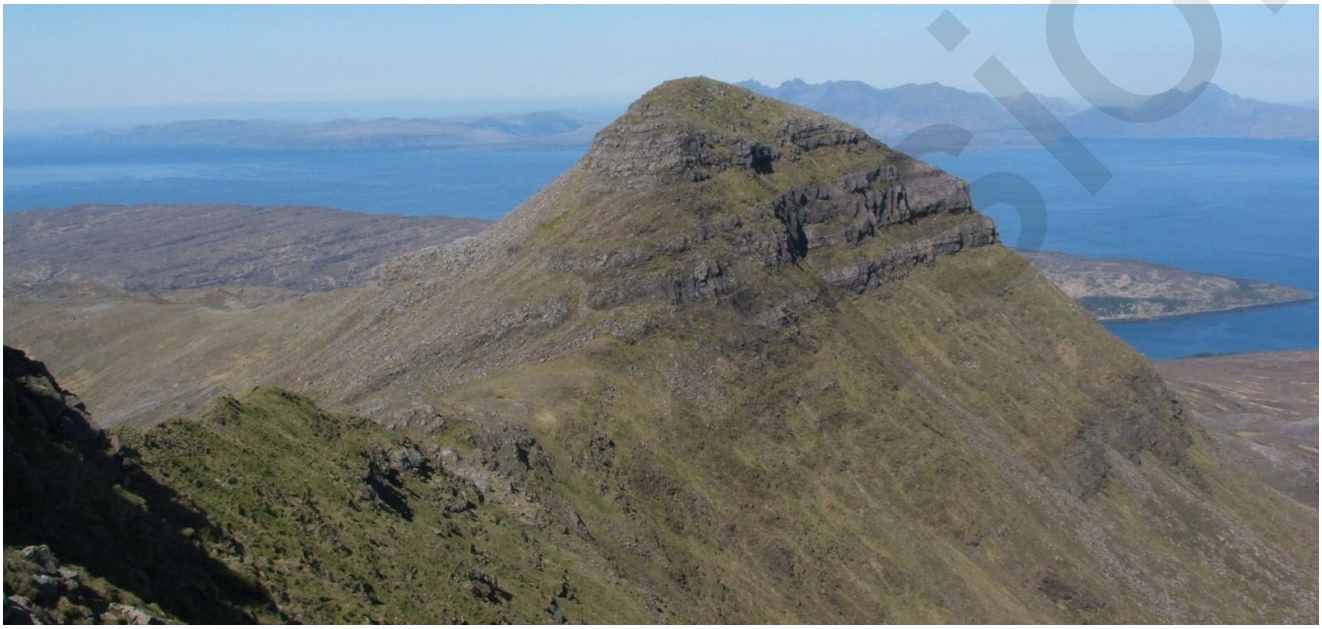


Figure 1-112: Layered peridotites and troctolites of the Rum Central Complex, forming Hallival, east Rum. View north towards Skye. [Photograph courtesy of David Brown]



Figure 1-113: Beinn Dearg Mhòr (left) and the twin summits of Glamaig (centre), all dominated by granites, Red Hills, Skye. View towards the south from Raasay.

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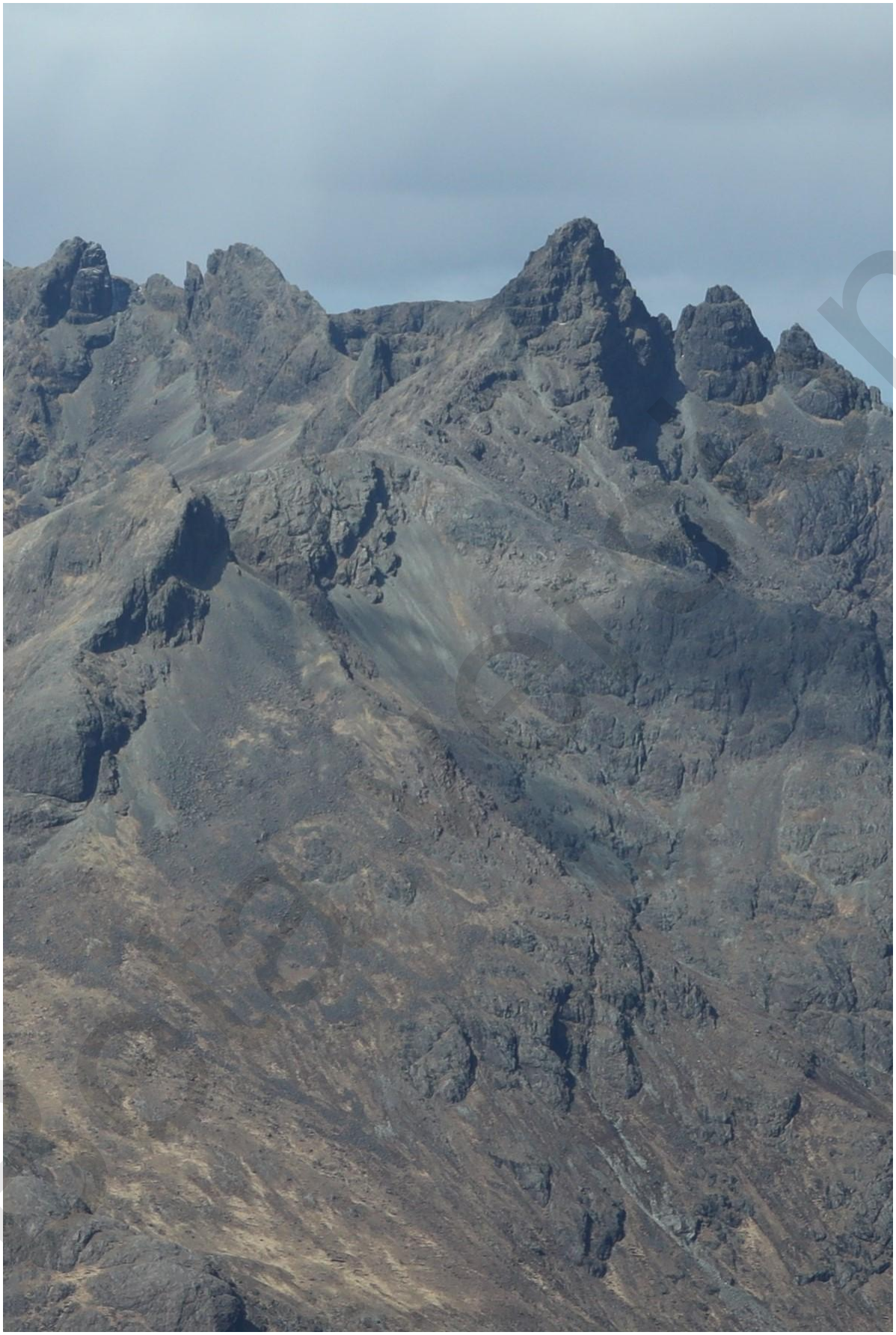


Figure 1-114: Gabbros and cone-sheets of the Northern Cuillin, Skye.

Limited radiometric ages and palaeomagnetic determinations indicate that the individual lava fields most likely accumulated over periods of a little over one million years, possibly less, and that the active life of individual central volcanoes (i.e. central complexes) may also have been similarly short.

The siting of the central complexes is not fully understood. J E Richey of the Geological Survey, responsible for much of the early work on this subject in Scotland, also examined several of the central complexes in Ireland. He highlighted the possible significance of the proximity of the central complexes to major pre-Paleocene faults; contributory factors include the intersection of these major faults with intra-basin ridges of Precambrian rocks, with the diapiric rise of bodies of granitic magma focussing subsequent basaltic magmatism, and the intersection of dyke swarms with intra-basin ridges, possibly facilitating the initiation of granite magmatism.

Overall, the most striking feature is the similarity of the magma composition and emplacement style across a wide range of structural settings and terranes, suggesting a region-wide stress field and a widely available heat source. The heat source is largely attributed to proto-Iceland mantle plumes. When a plume impinged on the area, large amounts of relatively buoyant basaltic magma were formed by decompressional melting. As this magma rose up to and through the continental crust, it ponded at 'traps' caused by relatively abrupt density changes across major structural discontinuities. Upward movement became progressively more influenced by the local geology and structure the closer the magma approached the contemporaneous Earth's surface. These factors enabled magmatic differentiation and contamination of the magmas and focussed their paths during ascent. The magmatism of the HIP switched off as ocean floor spreading was initiated to the NE.

Throughout the Oligocene and Miocene epochs, weathering and erosion were dominant, removing the upper and marginal sections of the lava fields and the upper volcanic (vent) parts of the central complexes. Much of the detritus was shed into sedimentary basins off NW Scotland.

The next major events recorded in the onshore geology of the Inner Hebrides and beyond are Quaternary Period glaciations. Much of the area, including the seabed, was blanketed by the extremities of a thick Late Devensian ice cap that formed over the central and northern Highlands 29,000 to 14,700 years ago. Following the ensuing decay of this ice sheet, the higher mountains of Skye, Rum, Mull and Arran supported corrie and valley glaciers during the Loch Lomond Stadial, 12,500 to 11,500 years ago (Figure 1-115; Figure 1-116; Figure 1-117). These glaciations are responsible for deposits of till, hummocky moraine and various glaciofluvial gravels. The accompanying changes in sea level are recorded in the raised marine beach deposits and marine notches that are common around coastlines.

The preglacial topography was drastically modified by deep erosion caused by the local ice caps and glaciers, most dramatically expressed in the deep rock basins and jagged skyline of the Cuillin on Skye, and which contributed to the excellent unweathered exposure now found in many of the corries and cliffs. Following the melting and retreat of the glaciers, over-steepened slopes collapsed, forming screes and extensive landslips, several of which are active to the present day (Figure 1-118; Figure 1-119; Figure 1-120).

Beta version



Figure 1-115: Ice-sculpted floor of Coir' a' Ghrunnda, Skye Cuillin. View towards the SW. Islands of Eigg (left) and Rum (right) in the distance.



Figure 1-116: Ice-sculpted lip between Loch Coir' a' Ghrunnda and Coir' a' Ghrunnda (left), Skye Cuillin.

Borrowdale

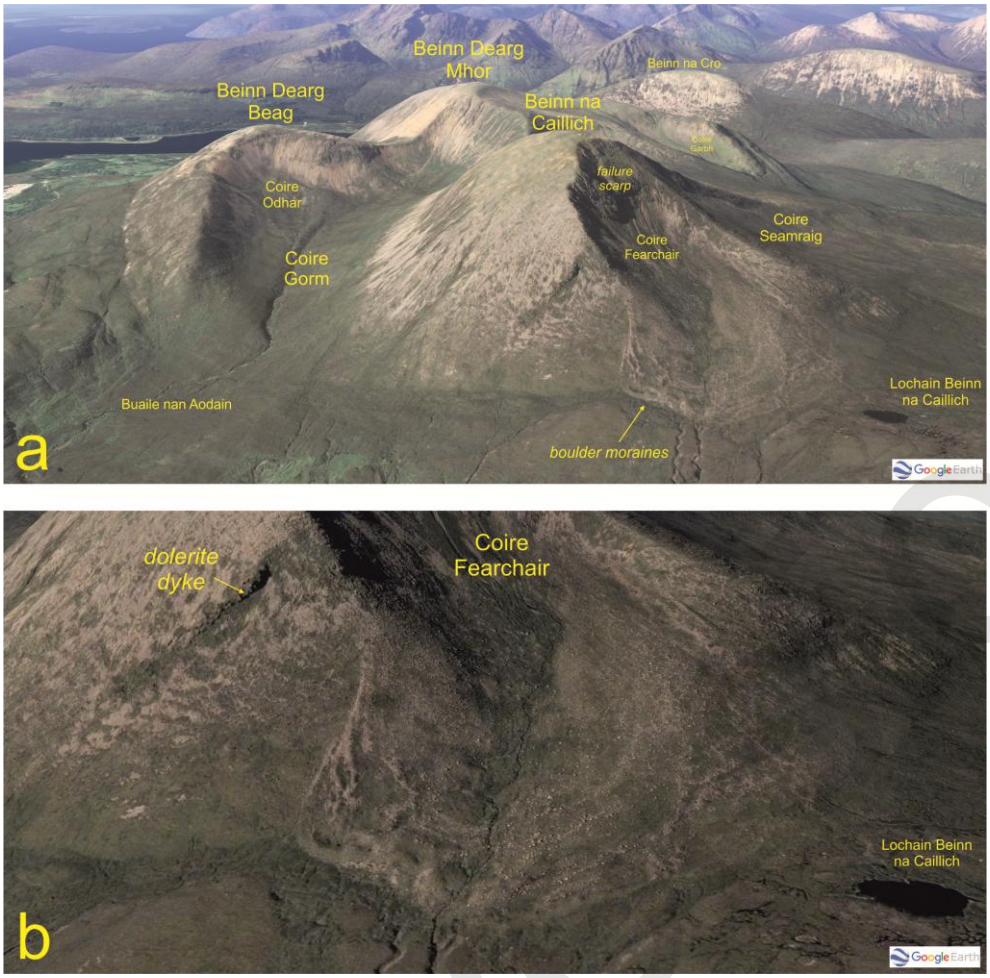


Figure 1-117: The Coire Fearchair boulder moraines, NE of Beinn na Caillich in the Red Hills, Strath, Skye. Oblique Google Earth© images. Views toward the SW.



Figure 1-118: Active landslides, Hallaig, SE Raasay.

Beta version



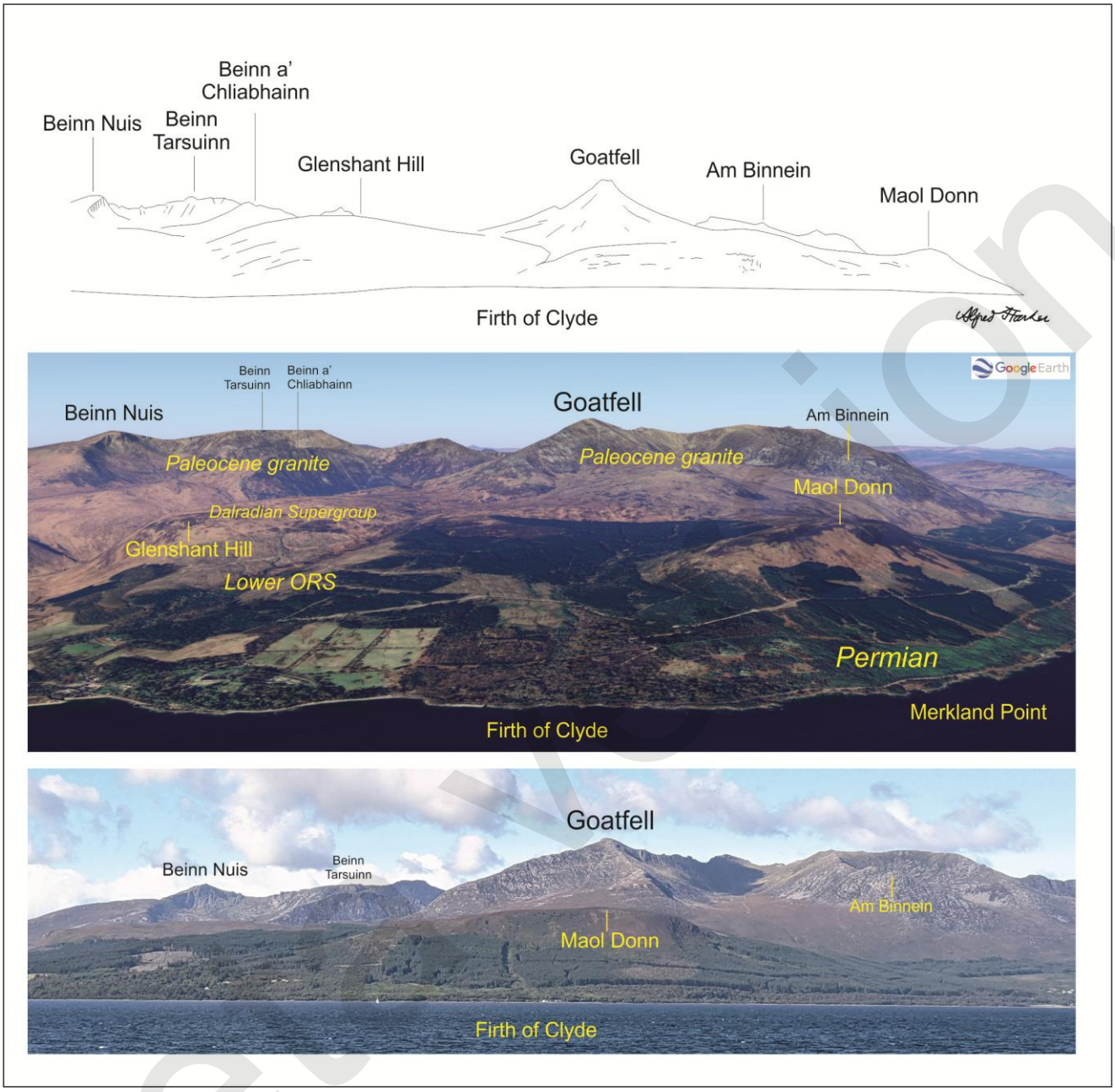
Figure 1-119: Landslipped inland escarpment of The Quiraing, Trotternish, Skye, composed of Paleocene lavas.



Figure 1-120: The Old Man of Storr and Needle Rock, landslipped blocks of lava that have detached from the The Storr cliff, Trotternish, Skye.

Beta version

2 Pre-Mesozoic Rocks



Pre-Mesozoic strata intruded by the North Arran Granite Pluton

2.1 Introduction

Skye, Raasay and Rum are located at the southern end of the Moine Thrust Zone (MTZ), on the NW margin of the Caledonian Mountain (or Orogenic) Belt (Peach *et al.* 1907; Goodenough *et al.* 2024; Strachan *et al.* 2024). At its simplest, to the NW of the MTZ is the foreland suite of rocks of the Hebridean Terrane, comprising the basement Archaean Lewisian Gneiss Complex ('Lewisian') (Section 2.2), unconformably overlain by Late Proterozoic (or Neoproterozoic) Torridonian Supergroup ('Torridonian') strata (Section 2.3) of predominantly fluvial and lacustrine facies, in turn unconformably overlain by Early Palaeozoic (Cambro-Ordovician) shallow marine strata comprising relatively pure quartz-dominated sandstones, shales, and limestones and dolostones with chert concretions (Section 2.6). To the SE of the MTZ is the

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Northern Highlands Terrane, dominated by Late Proterozoic Moine Supergroup ('Moine') 'schists' (*s.l.*) (psammites and pelites) (Section 2.4).

The landscape unconformity between the Lewisian Gneiss Complex and Torridonian strata has considerable relief, with the boundary approaching, in places, a vertical attitude, indicating steep-sided palaeo-valleys on the gneissose landscape in the Proterozoic Eon. The unconformity below the Cambro-Ordovician sequence has virtually no relief.

During the Caledonian Orogeny (*ca*. 500-400 Ma), the Moine schists, a thick, complex sequence of quartz- and feldspar-rich meta-sedimentary rocks (psammites) and mica-rich meta-sedimentary rocks (pelites), which can be correlated with units within the Torridonian sequence (Krabbendam *et al*. 2021), were thrusted/translated during the post Caledonian Orogeny 'Scandian event' towards the NW over the foreland sequence.

The Moine meta-sedimentary rocks are everywhere in tectonic/thrusted contact with rocks of the foreland sequence, the so-called 'belt of complication' of Peach *et al*. (1907), commonly referred to as the Moine Thrust Zone or Caledonian Front. Within this belt of complication, the units of the foreland sequence, together with the Moine schists, are in complex thrusted contact relationships, most usefully illustrated in cross-sections. The various thrust faults, or damage zones, comprise intensely deformed rocks, ranging from mylonites to cataclasites. Displacements on these thrusts range from a few kilometres, up to 30 km.

On Skye, thrusted rocks of the foreland sequence crop out on (the) Sleat (Peninsula), in the district of Strath, and at least as far west as Camasunary Bay. All of the units outlined above have, in some way, been modified and transported during the Caledonian Orogeny. However, on Raasay, the Lewisian Gneiss Complex is unconformably overlain by Torridonian strata, and neither unit appears to have been significantly affected by the orogeny, the classic relationship between the two lithologies in the foreland Hebridean Terrane.

On Rum, the distribution of many of the outcrops of the Lewisian and Torridonian rocks are complicated by their tectonic involvement with the Main Ring Fault, an important structure which developed during an early caldera-forming phase of the Paleocene Rum Volcano. However, the Torridonian strata in north Rum and south Rum, exterior to the Main Ring Fault, do not appear to have been tectonically disturbed and may form part of the Hebridean Terrane foreland.

The island of Iona, SW of Mull, comprises a geographically isolate fragment of the Lewisian Gneiss Complex overlain by strata that are interpreted to belong to the Torridonian Supergroup. To the east, across the Sound of Mull, is the Late Caledonian (*ca*. 414 Ma) composite (granite-diorite) Ross of Mull Pluton (Section 2.7). The eastern margin of this pluton has a contact aureole with country-rock Moine Supergroup psammites, pelites and amphibolites. These Moine rocks have an eastern faulted contact with Paleocene lavas.

South of the Great Glen Fault, the Grampian Terrane comprises complexly folded and thrusted psammites and pelites of the Late Proterozoic to Early Palaeozoic Dalradian Supergroup ('Dalradian') (Section 2.5), originally deposited as marine sands, silts, muds and limestones. These rocks constitute the regional basement. The grade of regional metamorphism is typically low to medium (Greenschist Facies) and original sedimentary features have survived the Grampian Orogeny that caused the deformation and metamorphism. These rocks, in the context of their distribution within the Palaeogene Volcanic Districts, are restricted to north Arran, where they have been subsequently deformed by the emplacement of the Paleocene North Arran Granite Pluton.

Beta version

On Arran, a small, fault-bounded outcrop of Ordovician pillow lavas and associated cherts and tuffs (Section 2.6) is interpreted as a fragment of obducted oceanic crust, the product of the closure of the Iapetus Ocean in the Early Palaeozoic, penecontemporaneous with the compressional events of the Grampian Orogeny.

Unconformably overlying the basement Dalradian rocks on Arran are strata referred to as the Old Red Sandstone (ORS), of Mid Silurian to Early Carboniferous age, deposited as post-orogenic alluvial fan, fluvial and lacustrine sequences in response to Caledonian orogenic uplift (Section 2.8). Basin development continued through the Carboniferous Period with coastal and shallow marine deposition and contemporaneous volcanism (Section 2.9). A return to terrestrial sedimentation took places in the Permian and Triassic periods, with deposition of continental interior 'red bed' aeolian and associated strata.

2.2 Archaean Lewisian Gneiss Complex

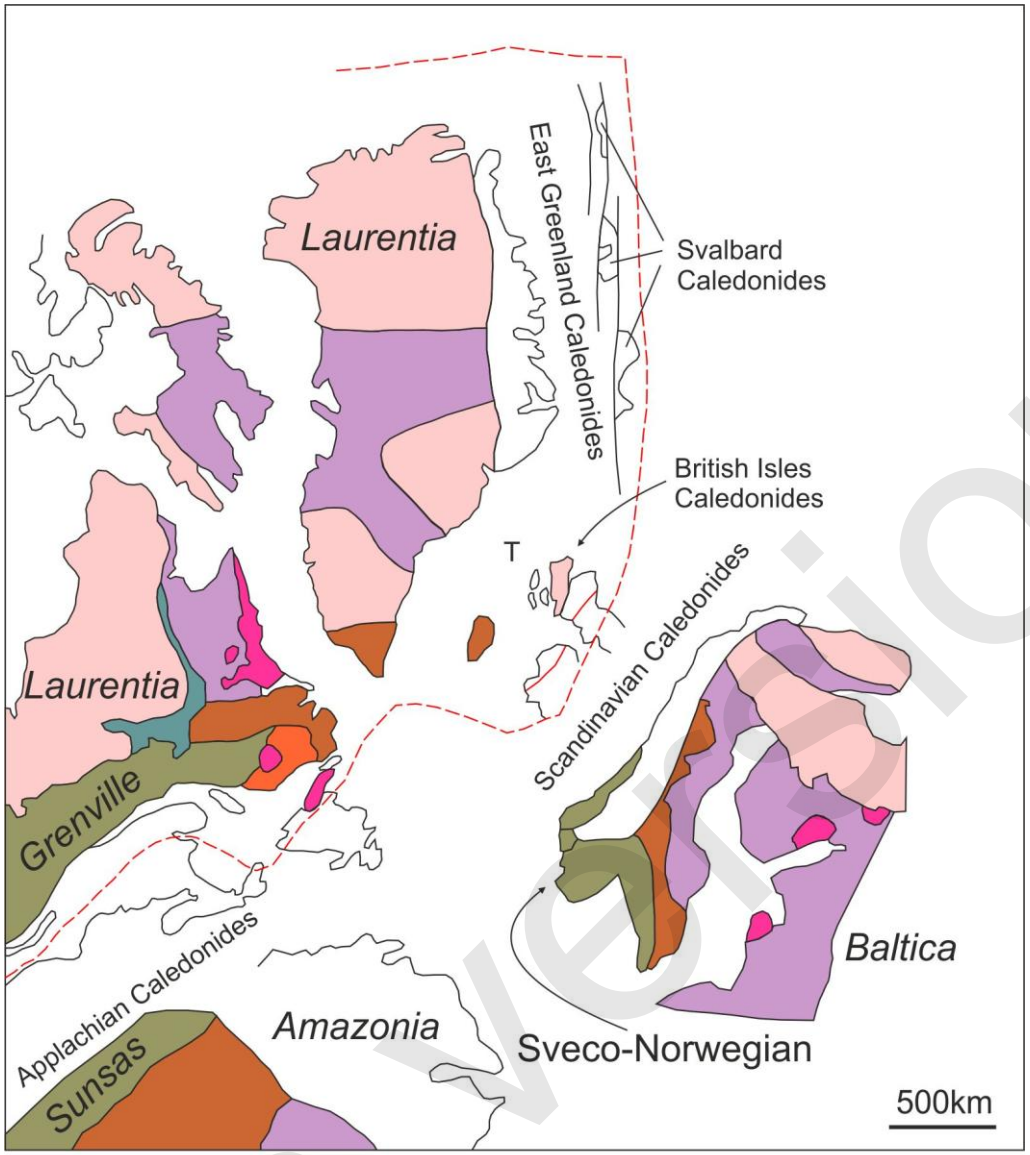
The Lewisian Gneiss Complex crops out in the northern part of the Hebridean Igneous Province (HIP), with the main occurrences on Raasay, Rona, Skye and Rum (Figure 2-1; Figure 2-2). The Raasay and Rona outcrops are interpreted to be the undisturbed basement of the foreland Hebridean Terrane, part of the Laurentian continental domain, correlating with major outcrops in Greenland and North America (Figure 2-1). The outcrops on Skye occur within the Moine Thrust Zone (MTZ) and the dismembered outcrops on Rum are complicated by their involvement with Paleocene caldera-associated faults.

These felsic orthogneisses gneisses were formed by high grade, Granulite Facies regional metamorphism, the Scourian (or Badcallian) Event (Goodenough *et al.* 2024), no later than *ca*. 2500 Ma, of tonalite, trondhjemite and granodiorite plutons (a TTG suite) that were intruded at lower crustal levels at *ca*. 3100-2800 Ma. Rare supracrustal assemblages, including metasedimentary and metavolcanic rocks, occur locally and provide evidence for early surface environments and sedimentary recycling (Goodenough *et al.* 2024). Following the Scourian Event, parts of the Lewisian Gneiss Complex experienced a further phase of deformation and metamorphism, commonly termed to as the Inverian Event. This event is less clearly defined than the Scourian Event and is recognised primarily through structural relationships, particularly the presence of deformation fabrics that pre-date a major mafic dyke emplacement event, but overprint earlier gneissic structures (Park *et al.* 2002). Intrusion of this suite of mafic (basaltic) dykes, the Scourie Dyke Swarm, occurred mainly at *ca*. 2400 Ma. This intrusive event was followed by fluid-assisted, pervasive deformation and Amphibolite Facies metamorphism ('reworking') that peaked about *ca*. 1700 Ma, commonly referred to as the Laxfordian Orogeny (or 'Event'). Rocks that experienced this event occur in the northern and southern portions of the Scottish Mainland outcrop, including the Raasay, Rona, Skye and Rum outcrops.

Detailed isotopic (U-Pb, single crystal) studies suggest further complexity, indicating that the outcrop of the Lewisian Gneiss Complex on the Scottish Mainland comprises an amalgamation of several crustal blocks, or terranes, each with a distinct protolith age and metamorphic history (Kinny *et al.* 2005). The Raasay, Rona, Skye and Rum outcrops are attributed to a Rona Terrane.

Subsequent retrogression, movement along shear zones and formation of crush belts occurred periodically during uplift and exhumation of the gneiss complex up to *ca*. 1100 Ma (Park 1991; Park *et al.* 1994; Goodenough *et al.* 2024).

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Grenville, Sveco-Norwegian & Sunas Orogenic Belts

Mesoproterozoic plutons

Granite-rhyolite terrane (1.5-1.3 Ga)

1.8-1.6 Ga orogenic belts

2.0-1.8 Ga orogenic belts

Pre 1.9 Ga continental supracrustal rocks

Archaean cratons

T, Torridonian Supergroup, NW Scotland

Figure 2-1: Proterozoic plate reconstruction for Skye and Raasay (after various sources).

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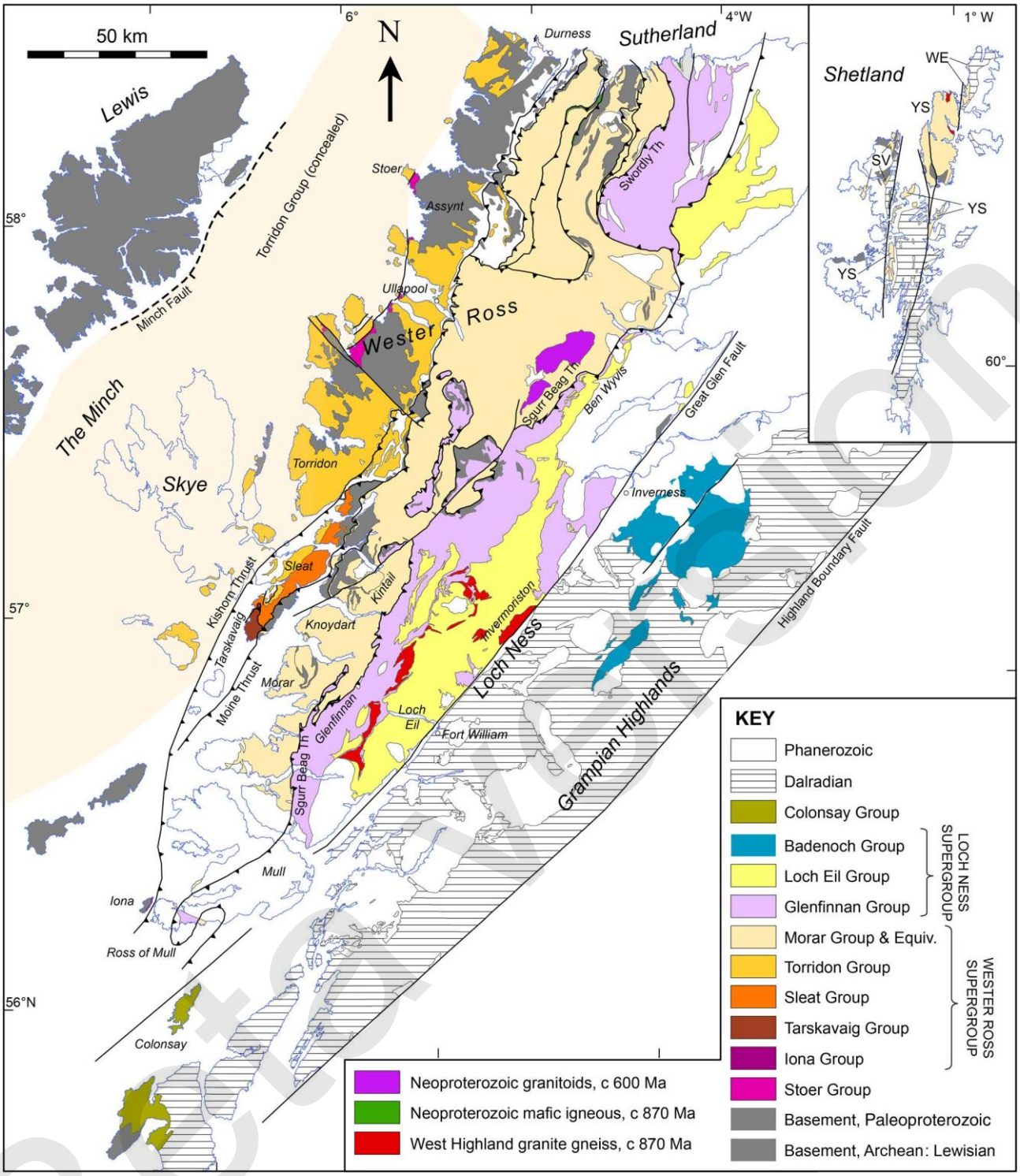


Figure 2-2: Geological map of Northern Highlands and Shetland (same scale) simplified after British Geological Survey (2007). In Shetland: SV, Sand Voe Group; WE, Westing Group; YS, Yell Sound. [Figure reproduced with permission from the British Geological Survey © UKRI 2025 All Rights Reserved. Source Krabbendam *et al.* 2021. DOI https://doi.org/10.1144/jgs2021-054. Permit Number CP25/041].

2.2.1 Raasay and Rona

High-grade, felsic, biotite-hornblende gneisses with mafic and ultramafic bands, lenses and clots crop out extensively on Raasay north of the Screapadal Fault and throughout Rona (Figure 2-3; Figure 2-4; Figure 2-5; Figure 2-6; Figure 2-7; Figure 2-8; Figure 2-9; Figure 2-10; Figure 2-11). These gneisses occur within the Hebridean Terrane, a term used to describe rocks NW of the Moine Thrust Zone that were not

affected by the Grampian Orogeny. Within the context of solely the Lewisian Gneiss Complex, Raasay and Rona gneisses are attributed to the Rona Terrane, with a protolith dated at 3125 - 2820 Ma, and underwent intense Amphibolite Facies metamorphism/reworking at *ca*. 1670 Ma (the Laxfordian Orogeny) and are similar to gneisses in the Applecross – Loch Torridon area of the Scottish Mainland. These gneisses are unconformably overlain by Torridonian Supergroup strata on the west side of north Raasay.



Figure 2-3: Typical exposure of the Lewisian Gneiss Complex in north Raasay, viewed towards the NNE across Loch an Uachdair. In the immediate area, around the shore of the loch, the bedrock is poorly exposed Torridonian Supergroup strata that unconformably overlie the Lewisian Gneiss Complex.



Figure 2-4: View north from Beinn na h-Iolaire of the Lewisian Gneiss Complex of north Raasay with, beyond, Rona.

Beta version

The Raasay gneisses are locally migmatitic and contain discontinuous layers/bands of basic-ultrabasic material (Figure 2-5; Figure 2-6; Figure 2-7; Figure 2-8; Figure 2-9; Figure 2-10). The foliation/layering typically has a NW-SE strike, with a highly variable dip. Granitic sheets and pegmatites are relatively common, indicating affinities with the southern outcrop(s) of the Scottish Mainland. Several dykes of the NW-SE -trending Paleocene Skye Main Dyke Swarm dissect the gneisses of north Raasay and Rona, giving rise to significant clefts and coastal inlets.



Figure 2-5: Typical complexly folded granitic gneiss on the southern slopes of Beinn na h-Iolaire, Raasay. Pole *ca*. 1 m long.

Beta



Figure 2-6: Exposure of folded, banded gneiss, with contrasting pale granitic and dark mafic (amphibolite) layers, south of Beinn na h-Iolaire, Raasay. Pole *ca*. 1 m long.



Figure 2-7: Typical banded gneiss of the foreland Lewisian Gneiss Complex in north Raasay, forming a road-cut and coastal exposures at Loch Arnish, south of Rubha Croin. The predominantly orange rocks are quartz-alkali feldspar -dominated felsic (granitic) gneiss, and the dark bands commonly forming discontinuous (boudinaged) masses, are mafic gneiss, dominated by amphibole and plagioclase.



Figure 2-8: Detail of typical banded gneiss of the foreland Lewisian Gneiss Complex in north Raasay, in a road-cut at Loch Arnish, south of Rubha Croin. The predominantly orange rocks are quartz-alkali feldspar - dominated felsic (granitic) gneiss, and the dark bands commonly forming discontinuous (boudinaged) masses, are mafic gneiss, dominated by amphibole and plagioclase. Pole *ca.* 1 m long.



Figure 2-9: Detail of typical banded gneiss of the foreland Lewisian Gneiss Complex in north Raasay, in a road-cut at Loch Arnish, south of Rubha Croin. Pole *ca.* 1 m long.



Figure 2-10: Detail of typical banded gneiss of the foreland Lewisian Gneiss Complex in north Raasay, in a road-cut at Loch Arnish, south of Rubha Croin. Pole *ca.* 1 m long.



Figure 2-11: Detail of typical banded gneiss of the foreland Lewisian Gneiss Complex in north Raasay, at Creag an Eoin, South Caol Fladda. Pole *ca.* 1 m long.

2.2.2 Skye

On Skye, the most extensive outcrops of Lewisian gneisses occurs on Sleat (Figure 2-12; Figure 2-13; Figure 2-14; Figure 2-15; Figure 2-16). These rocks are on the western edge of the Caledonian fold-belt within the Moine Thrust Zone and have been overthrust to the WNW as part of the Moine and Tarskavaig thrust sheets. They consist of sheared and retrogressed granitic gneisses with prominent amphibolite and zoned ultramafic pods. Near Isle Ornsay and on the shores of Loch na Dal, the mafic gneisses locally contain garnet porphyroblasts, and both mafic and felsic gneisses are overprinted by needle-like crystals of actinolite up to 5 cm in length. In the west, around Tarskavaig, thin, mylonitised layers of Lewisian-like gneiss crop out close to some thrust planes.

Several zoned ultramafic pods occur within the gneiss between Knock Bay and Isle Oronsay and consist of cores of talc and dolomite (commonly with magnetite), rimmed by succeeding zones of actinolite and biotite. Most of these pods tend towards lenticular forms, parallel to the foliation of the enclosing gneiss and formed by reaction between ultramafic intrusions and the country-rock gneisses during a period of regional metamorphism (either in Proterozoic or Lower Palaeozoic times).

Also of probable igneous origin is a band of highly altered serpentinite that trends NE-SW between Knock Bay and Camascross and can be traced along strike for a distance of at least 2 km. The serpentinite weathers to a rusty orange and is best exposed on the ridge to the west of Loch Baravaig (Barabhaig). Serpentine and Fe-carbonates dominate this rock, which also contains stringers of magnetite up to several millimetres wide.

The gneiss to the west of the Moine Thrust, at Tarskavaig, and further south on the north side of Gleann Meadhonach, shows a much greater degree of deformation. It lies above the Tarskavaig Thrust (and the associated Caradal and Lamascaig faults) and has been intensely deformed. This is best observed on the coast *ca*. 1.5 km south of Tarskavaig Bay, where the gneisses are intimately associated with Moine psammites and pelites.

In the vicinity of the Paleocene Eastern Red Hills Intrusive Centre (Chapter 9), at Creagan Dubh in Strath, an inlier of gneiss, unconformably overlain by Paleocene lavas and interbedded sedimentary rocks, crops out (Figure 2-17; Figure 2-18). The unconformity is somewhat irregular, but can be traced from the base of Creagan Dubh, NE to where it is exposed in the Allt na Teangaidh. The gneiss has a strong mineral banding/foliation, with alternating quartz-feldspar-rich and mafic portions and is, locally, brecciated or agmatitic. In thin-section, there is evidence that a melt phase developed: abundant micrographic intergrowths of quartz and alkali feldspar are present, suggesting that sufficient heat was available during the Paleocene igneous event to enable partial fusion to take place. Furthermore, breakdown of primary mafic minerals, pyroxene and amphibole, due to hydrothermal fluid circulation in the Paleocene, resulted in the extensive development of secondary chlorite and epidote.

Large (metre scale) xenoliths of gneiss are present in the ferrodiorite intrusion of the Marscoite Suite of the Paleocene Western Red Hills Intrusive Centre (Figure 2-19) (Chapter 9) (Wager *et al*. 1965; Thompson 1969). The more felsic components of these gneiss xenoliths have been partially melted, as have the gneiss xenoliths present in a dolerite intrusion on the NW side of Loch Sligachan.

Beta version

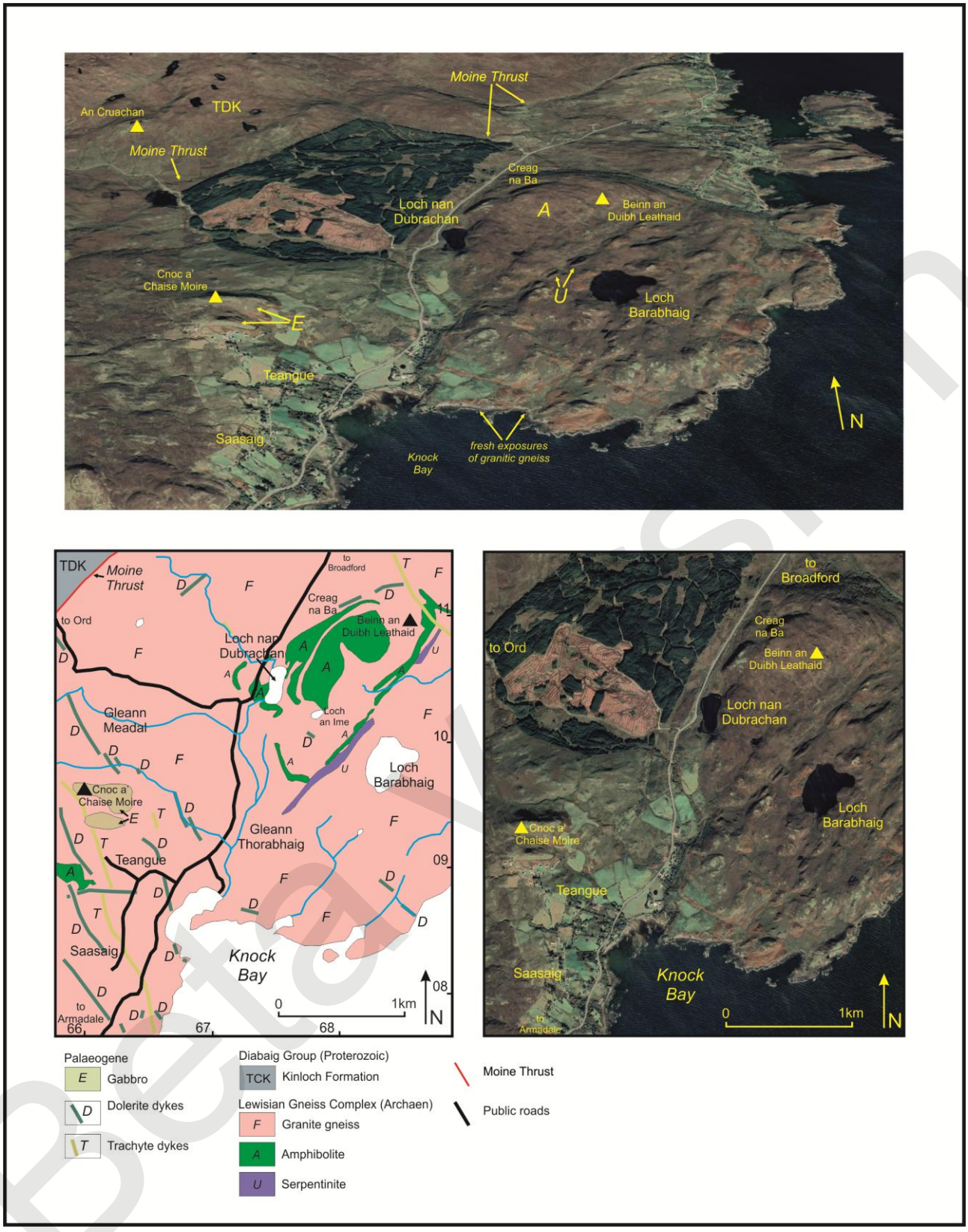


Figure 2-12: Simplified geological map and annotated Google Earth© images of the area around Knock, Sleat, Skye.

Beta version



Figure 2-13: Typical banded gneiss of the Lewisian Gneiss Complex within the Moine Thrust Sheet on the east side of Knock Bay, east coast of Sleat, Skye. The small-scale banded character of the gneiss may, in part, be due to Moine Thrust Zone deformation events. Pole *ca.* 1 m long.



Figure 2-14: Typical blue-grey serpentinite, brown on weathered surfaces. NW of Loch Barabhaig, Sleat, Skye. Pole *ca.* 1 m long.



Figure 2-15: Typical banded amphibolite, north Isleoronsay, Sleat, Skye. Pole *ca*. 1 m long.



Figure 2-16 : Mylonitised Lewisian gneiss within the Moine thrust sheet, Dùnan Ruadh, south of Kylerhea, Sound of Sleat.



Figure 2-17: Pale grey gneiss of the Lewisian Gneiss Complex inlier exposed in the Allt na Teangaidh, Strath, Skye. Pole *ca*. 1 m long.



Figure 2-18: Detail of the pale grey gneiss of the Lewisian Gneiss Complex inlier exposed in the Allt na Teangaidh, Strath, Skye. Pole *ca*. 1 m long.



Figure 2-19: Xenolith of banded Lewisian gneiss within the ferrodiorite intrusion of the Marscoite Suite, Western Red Hills Intrusive Centre, Skye, close to the base of Harker's Gully on the NW side of Marsco. Coin *ca*. 24 mm across.

2.2.3 Rum

Gneiss crops out at several localities on Rum, either immediately interior to or peripheral to the Main Ring Fault system, or adjacent to the central or western parts of the central complex (Figure 2-20; Figure 2-21). These gneisses, together with Torridon Group strata of the Torridonian Supergroup (see below) that unconformably overlie them, were uplifted by as much as 2 km during the Paleocene igneous activity. The more mafic components in the gneisses are commonly altered to two-pyroxene hornfelses, whereas the felsic gneisses show varying degrees of partial melting.

In the central complexes of Skye and Rum, gneisses are exposed at present, either because of doming and uplift due to igneous activity or because of faulting. These outcrops provide clear proof that these areas are underlain by the Lewisian Gneiss Complex, thus corroborating geophysical (seismic) evidence.

Gneiss clasts sourced from the uplifted country-rocks of the Rum Volcano (or Central Complex) are common within some conglomerates interbedded with lavas of the Paleocene Canna Lava Formation in NW Rum, Sanday, Canna and Skye (Chapter 6), but have not been affected by thermal metamorphism to the same extent as those found at outcrop in the Rum Central Complex.

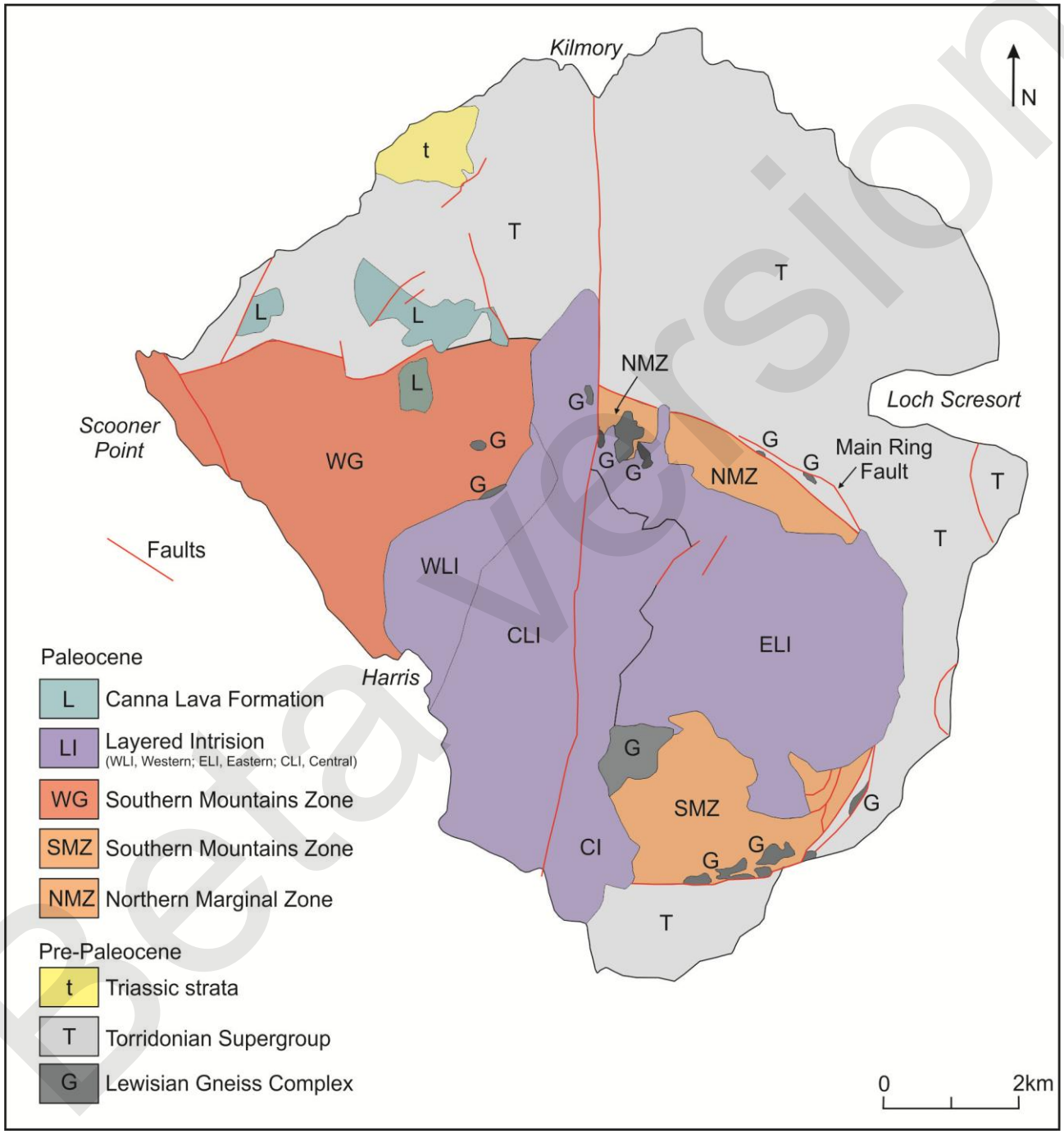


Figure 2-20: Simplified geological map indicating the locations of outcrops of (Lewisian) gneiss, predominantly associated with the Paleocene Northern Marginal Zone (NMZ) and Southern Mountains Zone (SMZ) suites of rocks and the Main Ring Fault.

Beta version



Figure 2-21: Banded granodioritic biotite gneiss with amphibolite layers of the Lewisian Gneiss Complex. East of the Priomh-lochs, central Rum. Person for scale. [Photograph courtesy of Henry Emeleus]

2.2.4 Iona

Granitic gneisses and rare pelitic (meta-sedimentary) gneiss and calcareous (meta-limestone, Iona Marble) gneiss crop out over much of western, southern and northern Iona and are attributed, along with gneisses on Coll and Tiree, as being part of the Lewisian Gneiss Complex (Figure 2-22; Figure 2-23; Figure 2-24; Figure 2-25; Figure 2-26; Figure 2-27; Figure 2-28; Figure 2-29; Figure 2-30; Figure 2-31). These banded gneisses have been dated (U-Pb on zircons) at *ca*. 2700 Ma, with younger granitic pegmatite sheets dated at *ca*. 1750 Ma (Goodenough *et al*. 2024). Members of the *ca*. 2400 Ma Scourie Dyke Swarm are represented (Figure 2-25). Subsequent Greenschist-Facies retrogression (epidotisation, hydrothermal alteration event(s)) is recognised (Figure 2-30), as is fault development at various levels in the crust during uplift (mylonite, pseudotachylite and cataclasite) (Figure 2-31). Although these events have not been accurately dated, their proximity to the margin of the Lower Palaeozoic Caledonian Orogenic Belt suggests a linkage.

Beta version



Figure 2-22: Typical 'gneiss topography', east coast of Iona.



Figure 2-23: Typical 'gneiss topography', west coast of Iona.

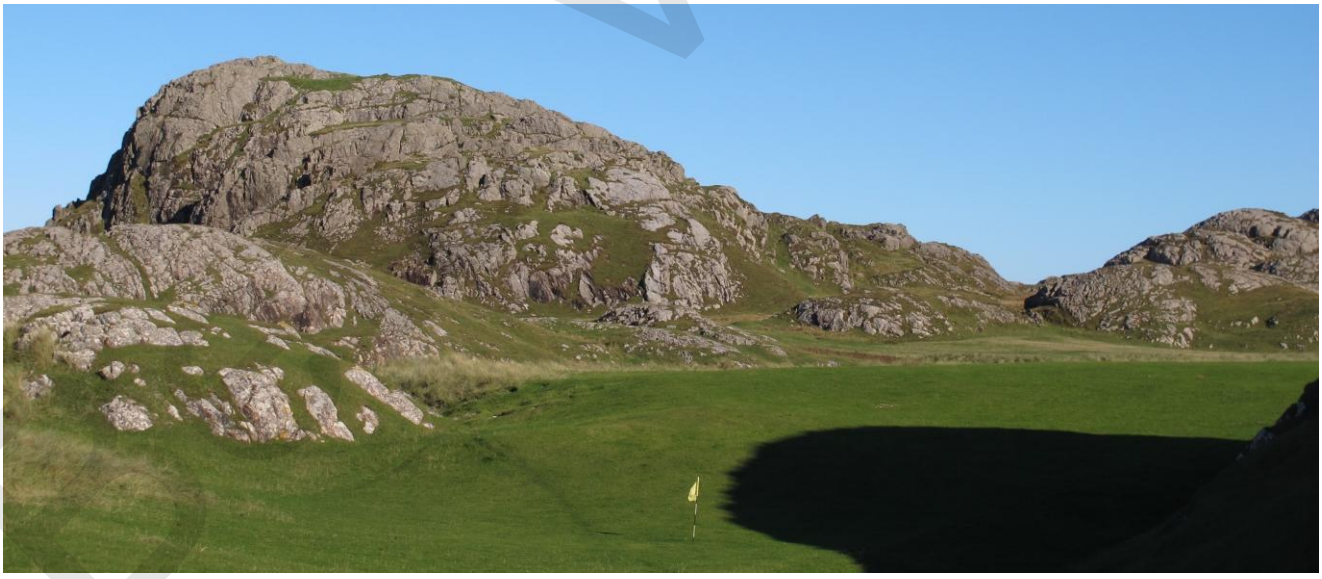


Figure 2-24: Typical 'gneiss topography', west coast of Iona. Golf green flag for scale.

Draft version



Figure 2-25: Amphibolitic gneiss with discontinuous layers of granitic gneiss, north Iona. Lens cap *ca*. 7 cm across.



Figure 2-26: Garnetiferous pelitic (meta-sedimentary) gneiss, west coast of Iona. Compass *ca*. 10 cm long.



Figure 2-27: Abandoned marble quarry ('Iona Marble'), with remnants of quarrying equipment. Port Carnan a' Ghille, SE Iona.

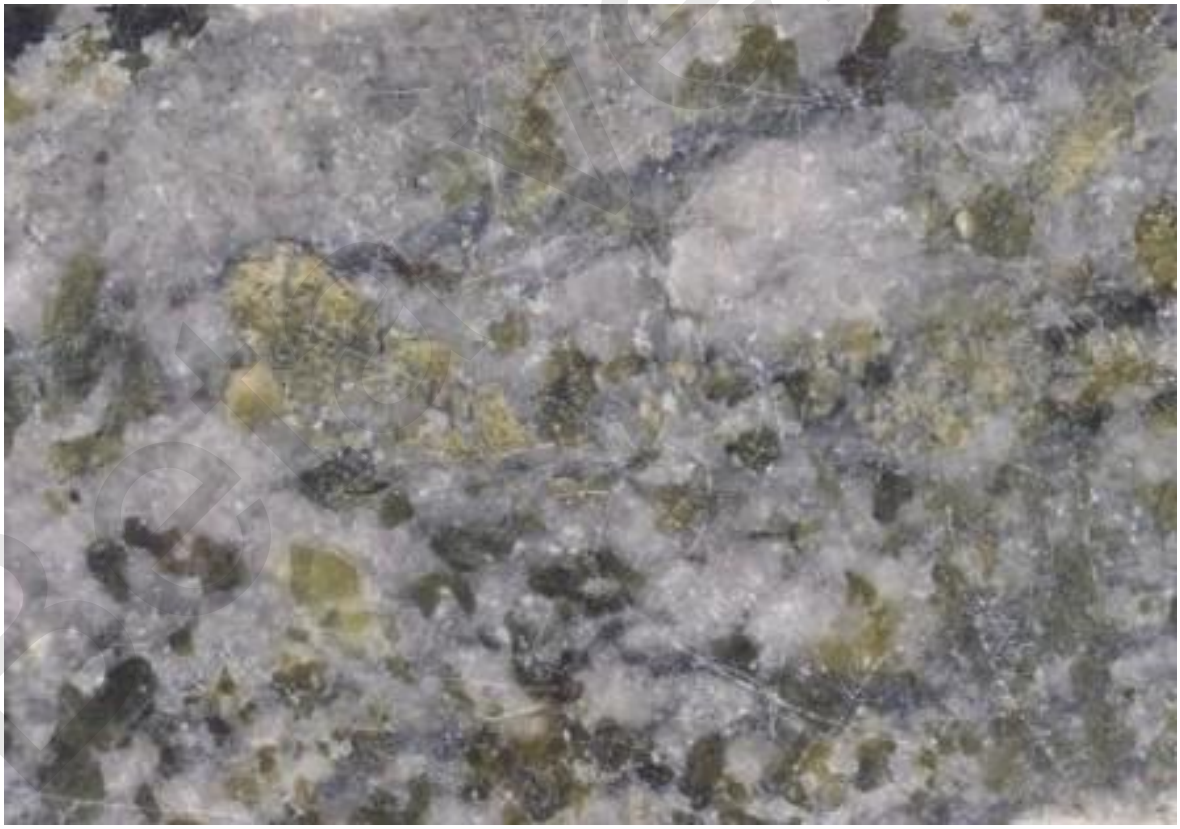


Figure 2-28: Cut surface of Iona Marble. View *ca*. 10 cm across. Serpentine after olivine, wollastonite and phlogopite are coloured; carbonate is white/grey.

Pre-version



Figure 2-29: Granitic gneiss intruded by a 'Scourie' dyke, north Iona. Fiona Fraser for scale.



Figure 2-30: Granitic gneiss with layers of amphibolite, the latter partially replaced by (green) epidote. Lens cap *ca*. 7 cm across.



Figure 2-31: Granitic gneiss disrupted by a network of fault-generated pseudotachylite. Pencil *ca*. 15 cm long.

2.3 Torridonian Supergroup

2.3.1 Introduction

The Torridonian Supergroup, commonly referred to as the 'Torridonian', comprises thick sequences of undeformed, non- to weakly-metamorphosed, Late Proterozoic (or Neoproterozoic) non- (or very near-shore) marine, clastic sedimentary rocks that overlie the Lewisian Gneiss Complex (e.g. Strachan *et al.* 2024) (Figure 2-32; Figure 2-33; Figure 2-34; Figure 2-35). These strata were deposited along the margin of the Laurentian continent in an extensional tectonic regime at a low palaeo-latitude. No significant biological activity had developed by the time these strata were deposited, from *ca.* 1200 to *ca.* 950 Ma, and which materially influenced transport and depositional processes. The basal unconformity records a prolonged period of pre-Neoproterozoic subaerial exposure and denudation, establishing a rugged basement topography prior to sedimentation. The nature of basal contacts varies regionally, reflecting differential erosion and structural inheritance from the Lewisian basement. The distinctive orange-brown coloration of many of the sandstones can, in part, be attributed to their high feldspar content, and, in part, to the presence of hematite in the cement.

Three subdivisions are recognised (Park *et al.* 2002; Strachan *et al.* 2024):

1. *The Stoer Group:* a *ca.* 2 km thick basal sequence ranging in sediment grade from conglomerate through to mudstone. Various facies, or depositional characteristics, are recognised, including: (a) a breccia facies, deposited in alluvial fans on a basement gneiss topography with up to 300 m of relief, with basal boulder beds of very local derivation, together with units containing rounded clasts suggesting kilometre-scale transport; (b) a muddy sandstone/arenite facies, a distal equivalent to the breccia facies, consisting of red-brown, massive sandstones and mud-rich sandstones and siltstones with desiccation cracks, deposited in mudflats; (c) a conglomerate facies, deposited in shallow braided river channels, with normal-graded, trough cross-bedded, coarse-grained sandstones and associated conglomerates; (d) a laminated sandstone facies, comprising mm-scale laminae of sandstone that define laterally-persistent, low-angle cross-bedded units up to 10 m thick, together with more massive sandstones with erosional bases, deposited in migrating subaqueous barchanoid (crescent-shaped) dunes and high-energy flood-water systems, respectively; (e) the so-called Bay of Stoer Facies, comprising red, trough cross-bedded sandstones with abundant soft-sediment deformation structures, deposited in a braided fluvial system; (f) the so-called Poll a' Mhuilt Facies, consisting of orange, laterally-extensive, metre-scale, fine-grained sandstones and siltstones with wave ripples and desiccation cracks, deposited in ephemeral lakes, and intercalated with the Bay of Stoer Facies; and, (g) the so-called Meall Dearg facies, comprising planar cross-bedded and planar bedded sandstones with wave-rippled surfaces, very similar to the Bay of Stoer Facies. The palaeolatitude was low, possibly 10-30° N (Strachan *et al.* 2024).

These various facies are clearly spatially and temporally related and vary significantly in thickness with position in the evolving sedimentary system. For example, the breccia facies formed alluvial fan deposits and talus aprons, located at or near to the base of the sequence, adjacent to basement palaeo-highs (i.e. hills at the time of sediment deposition). The conglomerate and laminated sandstone facies may be explained in terms of boulder and gravel fans fringing high ground, interfingered with fluvial deposits of ephemeral river systems, subsequently overwhelmed by a subaqueous barchanoid dune field. Abrupt changes in palaeo-flow directions and sporadic lacustrine deposits within predominantly fluvial intervals may be due to syn-depositional faulting, causing disruption to the drainage system.

Beta version

Rare volcanic rocks, comprising tholeiitic basaltic lavas, pyroclastic and volcaniclastic units, occur towards the top of the Stoer Group, principally within the Meall Dearg Formation, and represent a distinctive and temporally critical component of the succession. However, these rocks are geographically restricted to the Stoer–Assynt region of the NW Scottish Mainland. Irrespective, they provide a robust absolute age constraint of *ca*. 1,200 Ma (U–Pb and related methods) for the Stoer Group and, by extension, the onset of Torridonian sedimentation (Strachan *et al*. 2024). The palaeolatitude was in the range 10-30° N.

The Stoer Group has undergone relatively limited post-depositional modification. Diagenetic processes include compaction and cementation by silica and iron oxides.

2. *The Sleat Group:* up to 3.5 km of coarse-grained, grey sandstones and lesser amounts of grey fissile siltstones, taking its name from Sleat, SE Skye. The stratigraphic relationship between the Sleat Group and other Torridonian units is not straightforward. The Sleat Group is not demonstrably older or younger than the Stoer Group (see above) and may be partly time-equivalent, representing sedimentation in a separate but broadly contemporaneous basin system. These strata occur only within the Kishorn Thrust Sheet on Skye and are demonstrably older than the overlying, conformable Torridon Group (see below). Due to their location within the Moine Thrust Belt, these strata have been regionally metamorphosed, up to Lower Greenschist Facies, whereby original hematite is replaced by magnetite, hence their grey coloration. These strata are, however, not significantly deformed.

A number of formations are recognised:

[TOP]

The Beinn na Seamraig and Kinloch formations: two sequences of strongly distorted, cross-bedded sandstones (Beinn na Seamraig: coarse-grained; Kinloch: fine-grained). Typically, metre-thick sequences with ripple lamination, interbedded with grey shales. Interpreted as braided river deposits with intercalated lacustrine or shallow marine strata.

The Loch na Dal Formation: dark grey siltstones with laminae of coarse to very coarse sandstone, most likely of lacustrine or shallow marine origin, overlain by fluvial to deltaic channel-fill, trough cross-bedded sandstones.

Rubha Guail Formation: coarse green sandstones due to chlorite and epidote (formerly referred to as the *Epidote Grit Formation*), with trough cross-stratification, together with laminated, fine-grained sandstones and siltstones with wave ripples and desiccation cracks. Interpreted as the products of an alluvial fan prograding from the flank of a basement high into a lake.

[BASE]

Pebbles within the Sleat Group deposits are typically of silicic igneous rock lithologies, or of granitic gneiss, and have been relatively locally derived from an upper crustal source. However, compared with the Stoer Group, Sleat basins appear to have been more distal from active fault scarps or to have experienced lower rates of tectonic uplift. This interpretation is consistent with the reduced abundance of coarse clastic debris and the dominance of fine-grained sediment.

3. *The Torridon Group*: this sequence unconformably overlies the Stoer Group and also sits directly upon the Lewisian Gneiss Complex. It is the most extensive and volumetrically dominant component of the

Beta version

Torridonian Supergroup. The palaeo-topographic relief on the unconformity is substantial, up to *ca*. 600 m.

The climate during Torridon Group deposition is interpreted as semi-arid to arid, based on sediment colour, the presence of desiccation features, and limited chemical weathering of the feldspar-rich sandstones. The palaeolatitude was 20-30° S.

A number of formations are recognised:

[TOP]

Cailleach Head Formation: not represented on Skye or Raasay, this formation has a restricted outcrop on the Scottish Mainland and comprises sandstones and fissile siltstones, interpreted to have formed by deltas prograding into freshwater lakes.

Aultbea Formation: not represented on Skye or Raasay, consisting of medium-grained, red, trough and planar cross-bedded sandstones deposited in a braided river system towards the toe of an alluvial fan. The channels were typically very shallow, commonly < 10 m, and deposition occurred on transverse sand bars.

Applecross Formation: coarse-grained, red, trough and planar, cross-bedded, fluvial sandstones, typically with pebbles of various porphyritic igneous rocks and jasper. Grain-size grade diminishes towards the transitional top of the formation into the Aultbea Formation. Soft-sediment deformation features are relatively common, including within-bed synclines connected by cusps and folded cross-bedding/stratification, that are attributed to seismically induced liquefaction, or quicksand development. Interbedded fissile siltstones are interpreted as lacustrine deposits.

Diabaig Formation: four facies are recognised: (a) alluvial fan breccias, mantling the basement and infilling palaeo-valleys, dominated by clasts of gneiss; (b) fluvial, channel-filling trough and planar cross-bedded tabular sandstones, with wave-rippled surfaces, typically a few decimetres thick, with thin layers of red siltstone; (c) lacustrine, finely-laminated, grey siltstones with desiccation cracks and wave-rippled, fine-grained sandstones; and, (d) lacustrine, massive (i.e. ungraded) impure sandstones, up to several decimetres thick, with ripple laminations, interbedded with fissile siltstones with desiccation cracks.

[BASE]

One of the most important regional conclusions is that Torridonian sedimentation did not occur within a single basin, but rather within multiple basins of contrasting scale and tectonic control: the Stoer and Sleat groups accumulated in small, fault-bounded rift basins with strong local structural control, whereas the Torridon Group was deposited in a much broader, regionally integrated basin, characterised by thermal subsidence and limited syn-sedimentary faulting (Strachan *et al*. 2024). This spatial variability implies diachronous basin development and challenges older models of a simple, uniform Torridonian basin (Peach *et al*. 1907).

Regionally, Torridonian sandstones are arkosic to feldspathic, indicating rapid erosion and transport under conditions of limited chemical weathering. This is consistent with semi-arid to arid climates and high sediment supply rates. The persistence of feldspar through thick successions implies relatively short residence times in soils and fluvial systems, even in the large Torridon Group basin.

Where measurable, palaeo-current indicators show broad regional consistency, particularly within the Torridon Group, with dominant transport directions implying sediment supply from a wide hinterland to the west and north. This coherence supports the interpretation of large, integrated fluvial systems operating across the Laurentian margin during later Neoproterozoic time.

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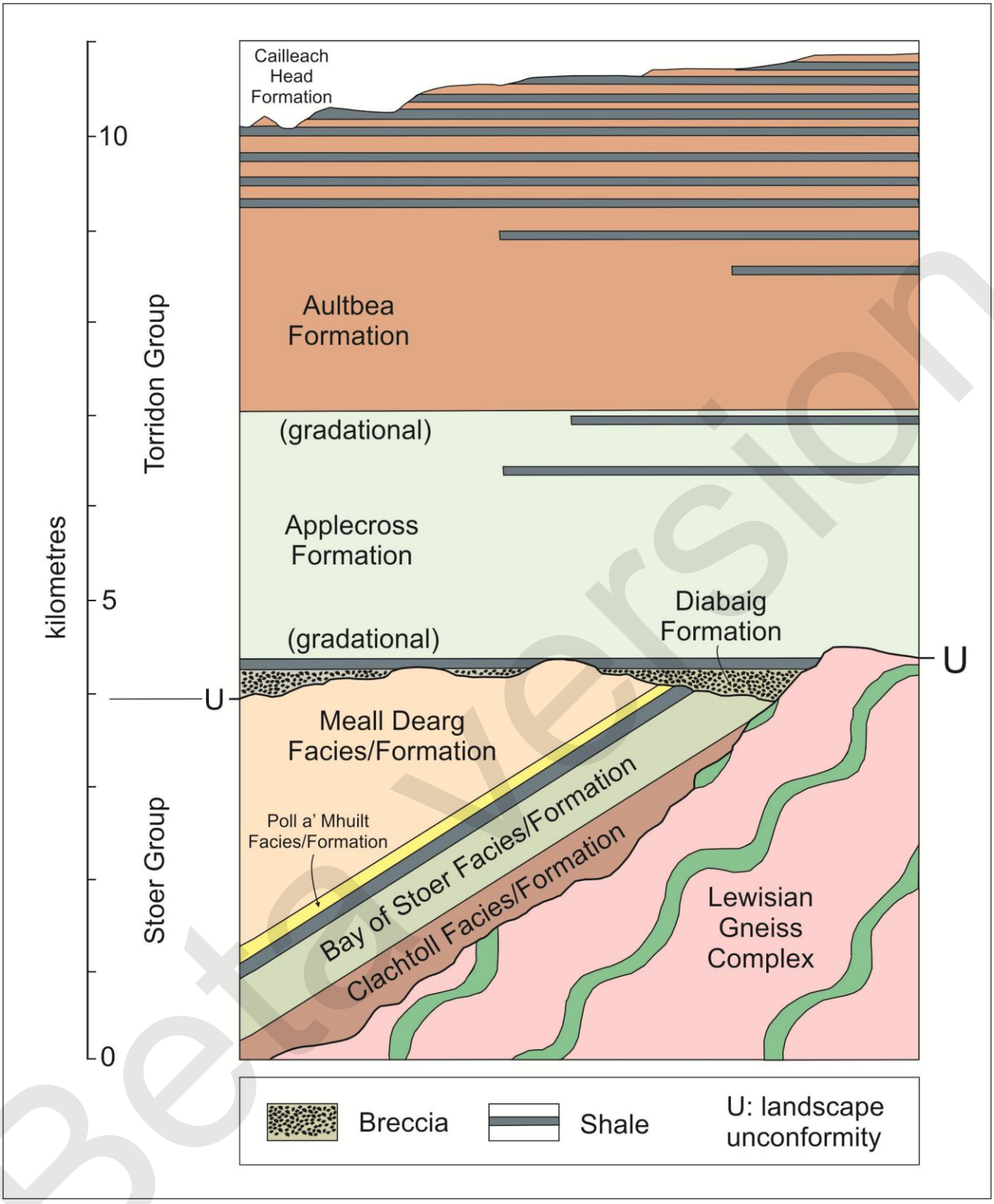


Figure 2-32: Lithostratigraphy of the Torridonian Supergroup (after various sources).

Only the Torridon Group crop outs as a foreland sequence on Rum, Skye, Scalpay, Raasay and Fladday; the Sleat Group is wholly restricted to the Kishorn Thrust Sheet on Sleat, SE Skye (Stewart 1991; Nicholson 1993).

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Figure 2-33: Stratigraphic nomenclature for Torridonian Supergroup strata of Skye, Raasay, Fladday and Rum.

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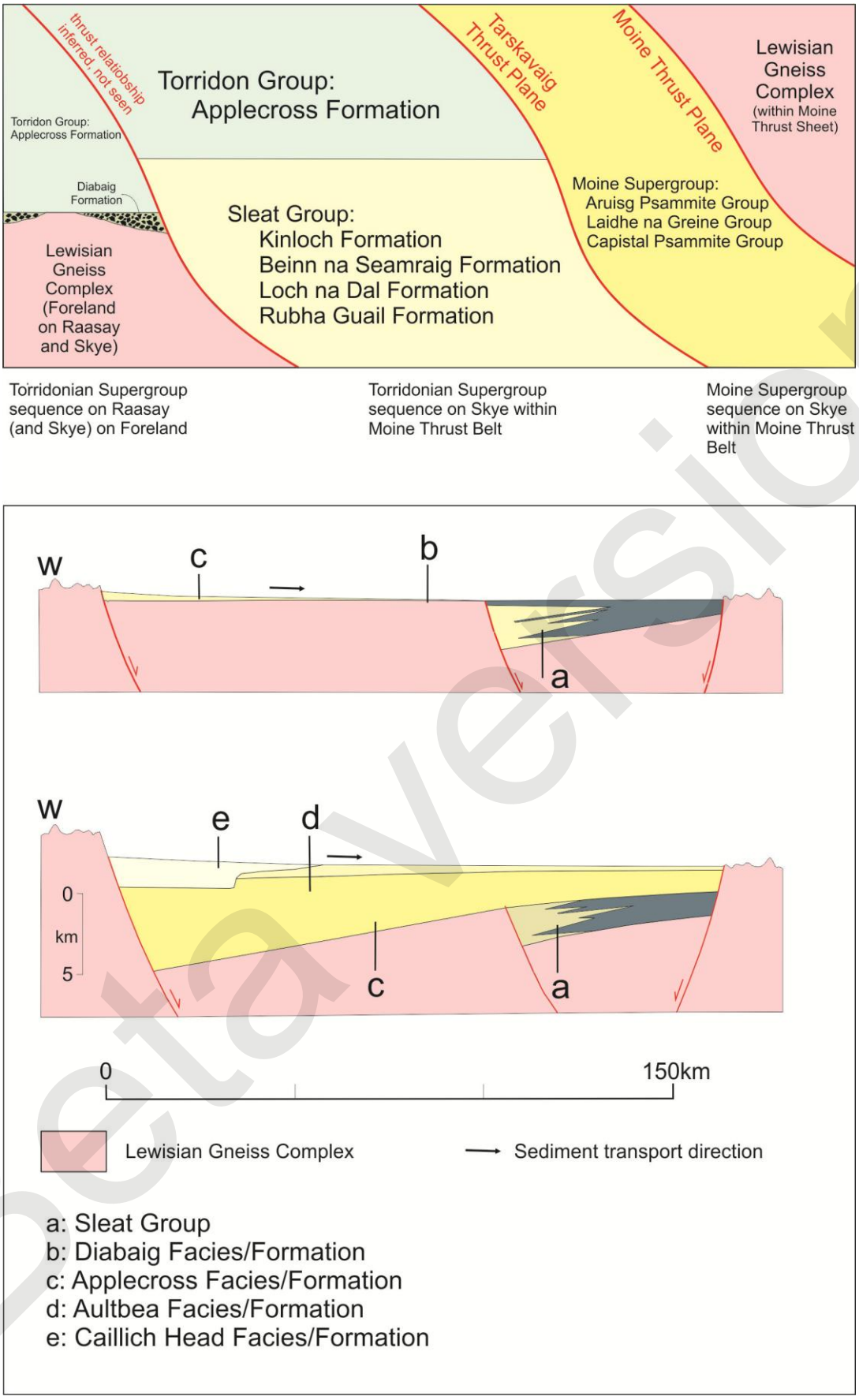


Figure 2-34: Distribution of Torridonian Supergroup strata on Skye and Raasay and a tectonic model for deposition (after Park *et al*. 2002).

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Figure 2-35: Distorted laminae (seismically induced; liquefaction/quicksand) within Leac-stearnan Member (Applecross Formation, Torridon Group) sandstones, east Soay. Pole *ca*. 1 m long.

Age determinations for the three recognised groups within the Torridonian are not easily achieved (Park *et al*. 2002; Strachan *et al*. 2024). A limestone within the Stoer Group yields a Pb isotopic age of 1199 ± 70 Ma and phosphate concretions within the Diabaig Formation at the base of the Torridon Group yield a Rb-Sr isotopic age of 994 ± 48 Ma and a Pb isotopic age of 951 ± 120 Ma (Turnbull *et al*. 1996). These data suggest a considerable age difference between the two groups, possibly as much as 200 m.y. There are no reliable isotopic ages for the Sleat Group, only identified within the Kishorn Thrust Sheet on Sleat, SE Skye, although stratigraphic relationships indicate it is older than the Torridon Group. The youngest detrital zircons in the Applecross Formation have a U-Pb date of 1060 ± 18 Ma (Rainbird *et al*. 2001).

The climate during deposition of the Torridonian is indicated from the rock record (Park *et al*. 2002; Strachan *et al*. 2024). For the Stoer Group, muddy sandstones in the Clachtoll Formation and massive siltstones in the Poll a' Mhuilt Member are interpreted to be very similar to present-day vertisols - soils with a high clay content that shrink and swell as their water content changes - and which are most commonly formed in warm, sub-humid or semi-arid climates. Consequently, a low latitude (within *ca*. 30° of the equator), an annual rainfall in the range 300-1200 mm and periods of (Summer) drought are implied. Palaeomagnetic data, and bulk-rock mineralogy and geochemistry point towards a similar interpretation. Given the age of the Torridonian Supergroup, weathering and erosion of the source rocks occurred on a landscape devoid of vegetation, very different to the present-day.

The overall tectonic-depositional model, proposed by Stewart (1982) and summarised by Park *et al*. (2002), for the Stoer Group, but also applicable to the Sleat and Torridon groups, involves a rift environment. The western margin of the basin is interpreted as the Minch Fault and the eastern margin a (precursor) fault that ultimately may have been transformed into the Moine Thrust Plane (Figure 2-2). The

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overall width of the basin was *ca*. 80 km and it received quartz and feldspar-rich detritus from the erosion of the (Lewisian Gneiss Complex) basement. During the deposition of the Applecross Formation strata, the dominant sediment transport direction was from the west, possibly influenced by movements on the Minch Fault (Figure 2-36).

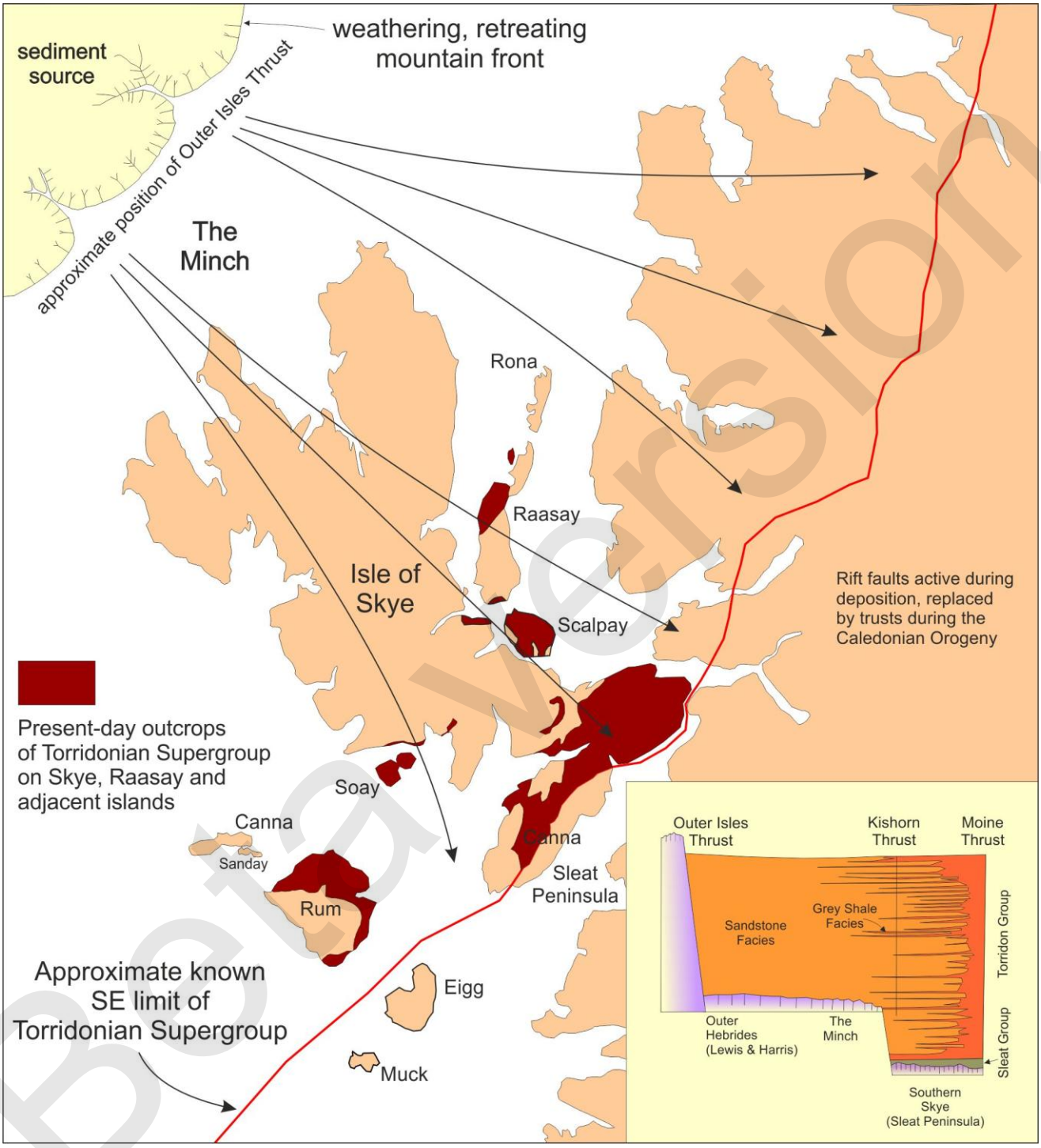


Figure 2-36: Map depicting outcrops of Torridonian strata on Skye, Raasay, Scalpay, Soay and Rum (after various sources).

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2.3.2 Raasay, Fladday, Scalpay and Skye: Foreland

On Raasay, Fladday, Scalpay, Soay and parts of Skye, the Torridonian sequence forms part of the tectonically undisturbed foreland of the Hebridean Terrane. The sequence ranges from (basal) breccias through to sandstones, siltstones and mudstones, and belong to the Diabaig Formation of the Stoer Group and the Applecross Formation of the Torridon Group (Figure 2-33).

Three sediment facies, based upon lithology, sedimentological characteristics, and colour, are recognised (Selley 1966):

1: A Basal facies, red or grey, comprising alluvial fan breccias, transported by water over a landscape with significant topography, dominated by boulder conglomerates and breccias, together with cobble and pebble conglomerates and very coarse sandstones. These very poorly stratified rocks are interpreted to have formed by relatively minor amounts of sediment transport and represent the eroded products of the underlying basement gneisses.

2: Red facies, due to hematite and quartz cement, typically pebbly, coarse, feldspathic arenites/sandstones and fissile siltstones with lenticular bedding, large-scale cross-bedding and distorted laminae due to seismically induced liquefaction, or quicksand development; a braided river environment of deposition is inferred.

3: Grey basal facies, due to chlorite and quartz cement, typically fissile siltstones dominant, but with some feldspathic arenites/sandstones, with small-scale cross stratification, grading, ripple structures and desiccation cracks; a lacustrine or nearshore marine environment of deposition is inferred.

On the basis of these facies characteristics, local sequences, or lithostratigraphic units, for Raasay, Fladday and Scalpay have been identified by Selley (1966) (Figure 2-37; Figure 2-38; Figure 2-39; Figure 2-40; Figure 2-41).

The Diabaig Formation on Raasay has a definable basal (Red facies) sequence of poorly sorted conglomerates and boulder beds, the Torran Member. The overlying Brochel Member (Raasay) and the (possibly correlatable) Caolas Fladday Member (Fladday) comprise dominant grey fissile siltstones (shales), together with sandstones. The presence of small-scale cross bedding, ripples and desiccation cracks are indicative of lacustrine or shoreline environments of deposition.

The upper part of the Diabaig Formation (Loch an Uachdair Member on Raasay and Lower Fladday Member of Fladday) is typical Red facies fluvial sequences, with large scale cross-stratification and spectacularly well developed (seismically induced) liquefaction/quicksand structures; the overall architecture of the facies indicates that the rivers were of the braided type.

The uppermost part of the preserved sequences on Raasay and Fladday belong to the Applecross Formation (Glames Member and Upper Fladday Member, respectively) and are predominantly of Red facies strata, sandstones with large-scale cross-bedding and thick beds with the liquefaction motif.

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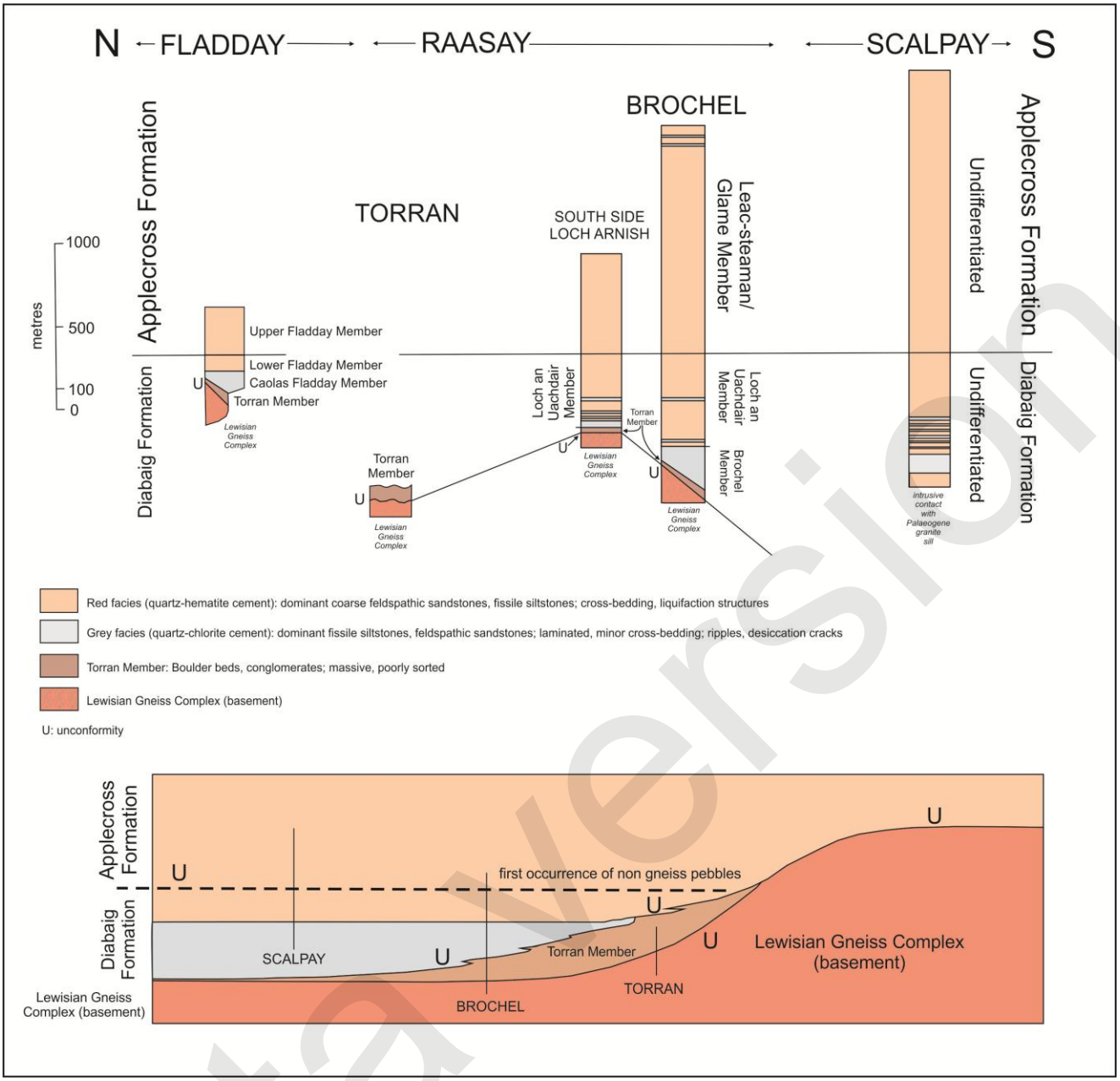


Figure 2-37: Stratigraphic logs and schematic distribution of depositional facies for Torridonian Supergroup strata of Skye, Raasay, Fladday and Scalpay (after Selley 1966).

Beta version



Figure 2-38: Coarse red sandstones of the Torridonian (Supergroup) Applecross Formation, with large-scale cross stratification and distorted laminae due to seismically induced liquefaction, or quicksand development, in a small (near-to-road) crag north of Glame, central-west Raasay, Pole *ca*. 1 m long.



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Figure 2-39: Distorted laminae (seismically induced; liquefaction/quicksand) within Loch an Uach(-dair) Member feldspathic sandstones, directly NW of Loch Beag, north Raasay. Pole *ca*. 1 m long.



Figure 2-40: Detail of distorted laminae (seismically induced; liquefaction/quicksand) within Loch an Uach(-dair) Member feldspathic sandstones, directly NW of Loch Beag, north Raasay. Pole *ca*. 1 m long.



Figure 2-41: Typical pebbly feldspathic sandstone (arkose), Torran Member, at tombolo on east coast of Eilean Fladday. Coin *ca*. 24 mm across.

The Torridonian strata on Scalpay have much in common with the Raasay and Fladday sequences, comprising both the Diabaig and Applecross formations (Figure 2-42; Figure 2-43). The base of the Diabaig Formation is missing due to the emplacement of a Paleocene granite in the SW of the island; the strata adjacent to the granite have been both thermally and hydrothermally altered. In general terms, both the Red and the Grey facies are present and are interbedded. The overlying Applecross Formation strata are, similar to Raasay and Fladday, of the Red facies, comprising sandstones with large-scale cross-bedding and thick beds with the liquefaction motif.



Figure 2-42: Scalpay from Glamaig.



Figure 2-43: Applecross Formation sandstones, siltstones and conglomerates, NE Scalpay.

Rocks of the Torridon Group that are attributed to the foreland sequence crop out around the northern margin of the Western Red Hills Intrusive Centre (Chapter 9) between Sconser and Maol na Gainmhich, at Rubh' an Uillt Dharaich, and around the Eastern Red Hills Intrusive Centre, for example south of Broadford, at Dunan. In addition, there are outcrops along the north side of Soay Sound, on Soay and in Camasunary Bay. They are generally red-brown feldspathic sandstones, commonly pebbly, and typical of the Applecross Formation (Figure 2-44; Figure 2-45; Figure 2-46; Figure 2-47; Figure 2-48; Figure 2-49; Figure 2-50; Figure 2-51; Figure 2-52).

Pre-version



Figure 2-44: The Sconser Quarry at Achadh Mòr, a source of hard rock aggregate from metamorphosed sandstones and siltstones of the Torridonian Sithean Glac an Ime Member of the Applecross Formation.



Figure 2-45: Coastal section east of An Leac on the north side of Soay Sound, Skye. The cliffs in the near distance are composed of reddish-orange feldspathic arenites of the Bheinn Bhreac Member, intruded by Paleocene dolerite dykes and sheets. The coastal cliffs in the distance are composed of the Leac-stearnan Member. Both are overlain by Paleocene basaltic lavas.



Figure 2-46: Reddish-orange feldspathic arenites of the Bheinn Bhreac Member, intruded by Paleocene dolerite dykes and sheets. View is north towards Skye on the north side of Soay Sound.

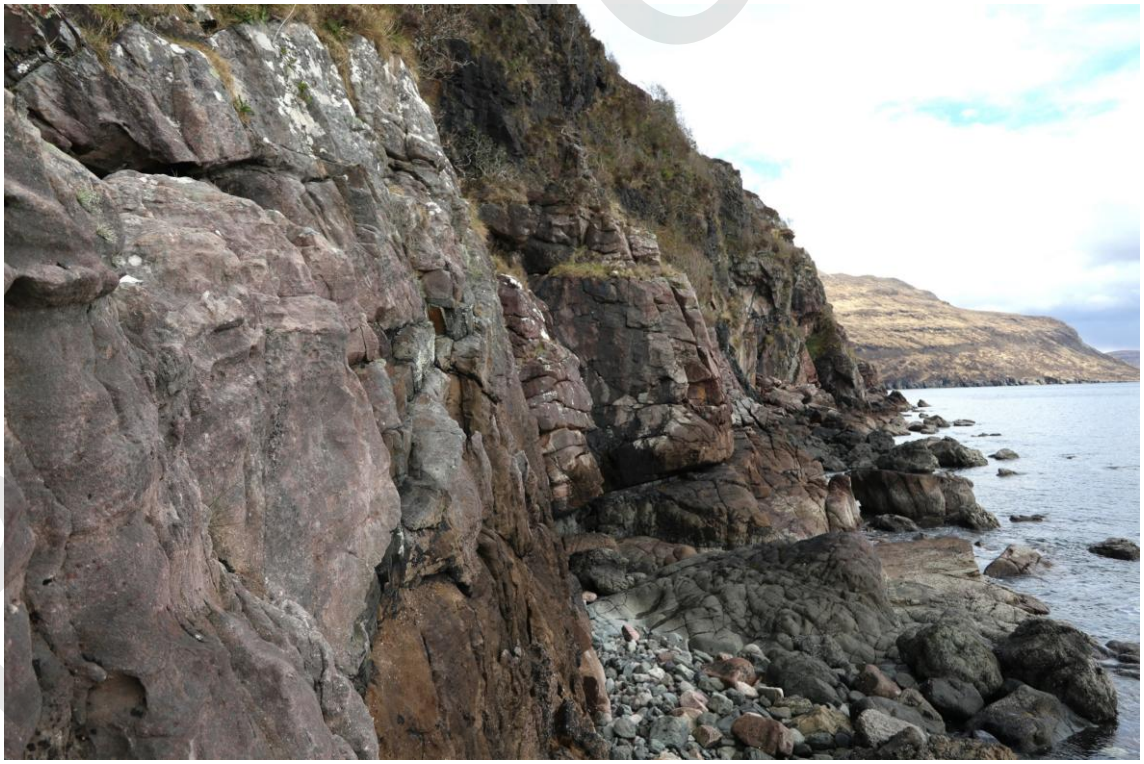


Figure 2-47: Tabular sheets of cross-stratified Bheinn Bhreac Member feldspathic arenite with thin layers rich in cobbles and pebbles of quartzite, felsite, andesite and jasper. North side of Soay Sound, Skye.



Figure 2-48: Typical coarse, pebbly feldspathic arenite within the Bheinn Bhreac Member on the north side of Soay Sound, Skye. Coin *ca.* 24 mm across.

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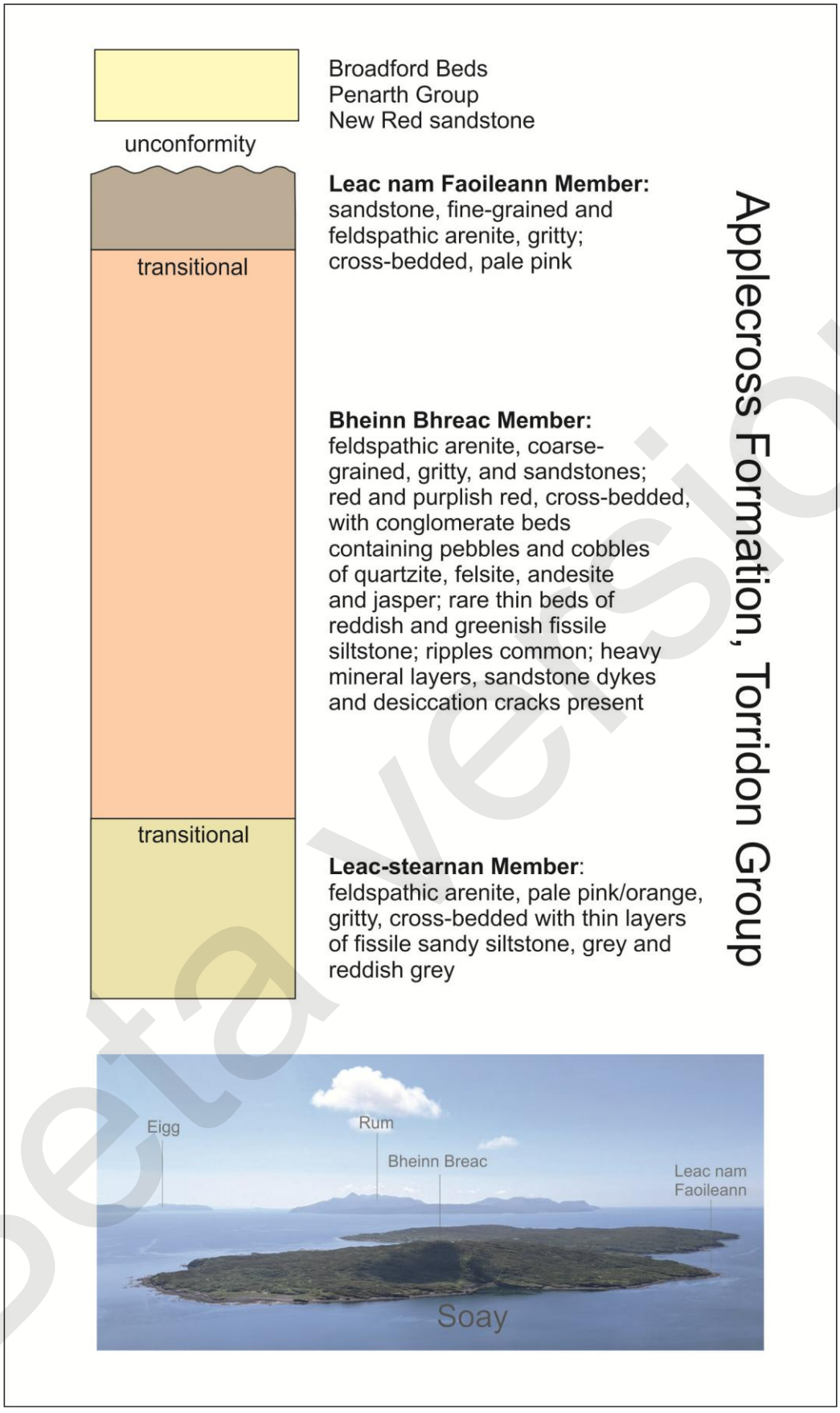


Figure 2-49: Lithostratigraphy of Applecross Formation strata, Soay.

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Figure 2-50: Inclined Bheinn Bhreac Member sandstones, east Soay, from Skye.



Figure 2-51: Cross stratified Leac-stearnan Member sandstones, east Soay. Pole *ca.* 1 m long.



Figure 2-52: Tabular, fine-grained sandstones, siltstones and shales with well-developed ripples in the Sgùrr na Stri Member, in the coastal section on the west side of Camas Fhionnairigh (Camasunary), Skye. Pole *ca.* 1 m long. Bla Bheinn in the distance.

2.3.3 Skye: Moine Thrust Zone

The Torridonian strata in SE Skye lie within the Kishorn Thrust Sheet of the Moine Thrust Belt and are much affected by faulting and thrusting (Figure 2-34).

An extensive tract of tectonically transported Torridonian strata occurs on Sleat and in isolated NW-overthrust sheets in the vicinity of Broadford. The oldest/stratigraphically lowest strata belong to the Sleat Group and consist of greyish green, grey and buff gritty sandstones, commonly epidote-bearing, together with fissile siltstones and sandy laminated siltstones. They comprise over 3000 m of strata and occur in a belt up to 7 km in width stretching from the shores of Loch Alsh, east of Kyleakin, and SW along Sleat to near Armadale. Overlying these strata, west of a line from around Ord to Kyleakin, are brownish red, cross-bedded feldspathic sandstones of the Applecross Formation.

The lowest exposed part of the sequence in the Sleat Group is the Rubha Guail Formation, formerly the Epidote Grit Formation, which crops out on the Sound of Sleat (Figure 2-53). The original name of this formation is derived from the presence of epidote and epidotised feldspar, commonly as constituents of pebbles, which represent eroded debris from the Lewisian Gneiss Complex. The sequence comprises very coarse to medium grade sandstones, as well as mudstones and shales, deposited from fast-flowing, braided rivers and in shallow lakes, respectively.

Beta version



Figure 2-53: Sandstones and siltstones of the Rubha Guail Formation, formerly the Epidote Grit Formation, Dùnan Ruadh, Sound of Sleat, south of Kylerhea, Skye. Pole *ca*. 1 m long.

Stratigraphically above the Rubha Guail Formation is a sequence of alternating coarse- and fine-grained sandstones, the Loch na Dal Formation, with abrupt variations in grain-size (Figure 2-54) (Peach *et al*. 1910). The presence of desiccation cracks, ripple-structures and fine laminations indicate deposition in some form of intertidal environment.



Figure 2-54: Steeply inclined, fine-grained, laminated sandstone of the Loch na Dal Formation, west side of Loch na Dal, Sleat, SE Skye. Pole *ca*. 1 m long.

Browser version

The Beinn na Seamraig Formation is dominated by thick-bedded, fluvial channel sandstones that commonly have well developed cross bedding, with foresets up to half a metre in height (Figure 2-55). Distortion of laminae is common, formed by seismically induced liquefaction during dewatering. Interbedded with these sandstones are thin beds of grey siltstones, most likely a lacustrine facies.



Figure 2-55: Beinn na Seamraig Formation sandstones on the north side of the Broadford-Kylerhea Road at the Bealach Udal, with distorted stratification due to seismically induced liquefaction during dewatering. Pole *ca*. 1 m long.

At the top of the Sleat Group is the Kinloch Formation (Figure 2-56), with a lower transitional boundary being defined as where the various units, both coarse- and fine-grained, become thicker (Peach *et al.* 1910). Cross-bedding and distorted lamination are common. At the top of the formation there is a return to thin-bedded, fine-grained sandstones and siltstones, which alternate with thick sandstone units.

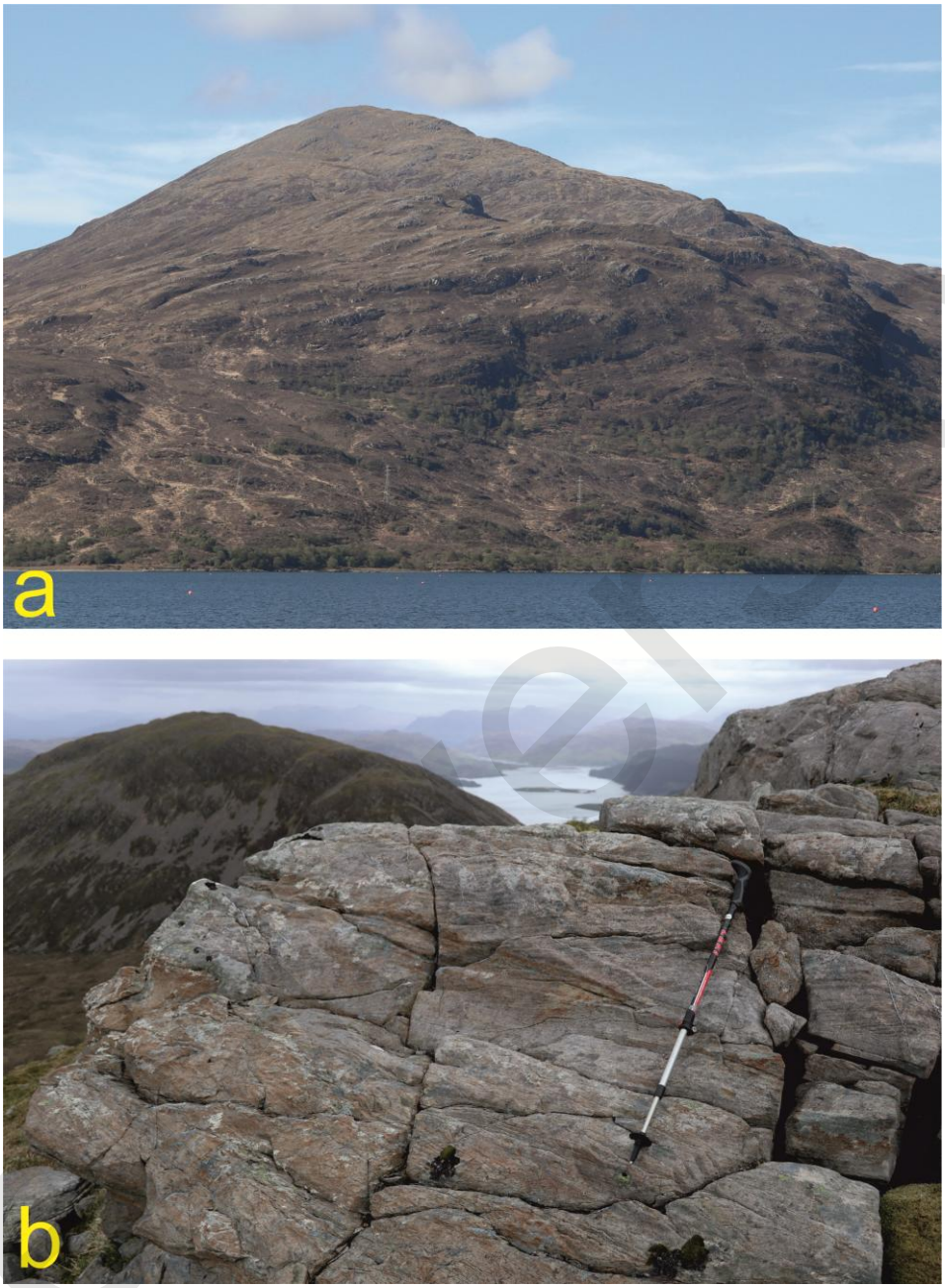


Figure 2-56: (a) Kinloch Formation sandstones forming the area NW of Beinn na Caillich (right of summit), south of Kyleakin, viewed towards the SW from the north side of Loch Alsh (on the Scottish Mainland); and, (b) inverted Kinloch Formation strata, indicated by truncated erosion surfaces, at the summit of Sgùrr na Coinnich, south of Beinn na Caillich. View up Loch Alsh towards ENE. Pole *ca.* 1 m long.

The overlying Applecross Formation of the Torridon Group is dominated by reddish-brown, medium-grained sandstones (Figure 2-57; Figure 2-58; Figure 2-59) and are exposed over a wide tract of ground running from Kyleakin to Loch Eishort, and in the area around Ord, and are interpreted as part of a sequence below the Kishorn Thrust Plane (Figure 2-34).



Figure 2-57: Applecross Formation sandstones within the Kishorn Thrust sheet, on the north shore of Loch Eishort, east of the deserted village of Boreraig, with distorted stratification due to seismically induced liquefaction during dewatering. Pole *ca*. 1 m long.



Figure 2-58: Applecross Formation sandstones within the Kishorn Thrust sheet, on the north shore of Loch Eishort, east of the deserted village of Boreraig, with distorted stratification due to seismically induced liquefaction during dewatering. Pole *ca*. 1 m long.

Borehole



Figure 2-59: Inverted ('younging' downwards), fractured Applecross Formation sandstones within the Moine Thrust Belt south of the Ord River, Sleat, Skye. Pole *ca*. 1 m long.

2.3.4 Rum

Torridon Group rocks dominate the north and east of the island, where a thick succession (> 2500 m), mainly reddish brown, feldspathic sandstones (arenites) and pebbly sandstones, belonging to the Applecross Formation is preserved **(**Figure 2-60**)**. These tabular sandstone bodies are interpreted as sandbars formed in a braided river system. The sequence now dips at 10-30° towards WNW (Figure 2-61**;** Figure 2-62; Figure 2-63). Within the member, the contrasting weathering and erosion of relatively coarse- and fine-grained beds, alternating on a scale of one to ten metres, produces a distinctive terraced landscape. To the south, near the Paleocene Main Ring Fault, a major structure related to the igneous rocks of the Rum Central Complex (Chapter 9), dips are more variable, commonly much steeper, and thermal alteration has modified primary mineralogies.

The underlying fluvio-deltaic sandstones and siltstones of the Allt Mor na h-Uamha Member (Applecross Formation) and the lacustrine fissile siltstones and sandstones of the Laimhrig Shale Member (Diabaig Formation) are restricted to the east side of the island.

The lowest of the Torridonian stratigraphic units, the Fiachanis Gritty Sandstone, is restricted to outcrops within (interior) the Main Ring Fault. The dominant lithologies are breccias and gritty sandstones, deposited by channelised flow and sheet floods within an alluvial fan system on an irregular topography of Lewisian gneiss. The distal depositional facies of these coarse-grained deposits are the fine-grained laminated beds of the Laimhrig Shale Member. Within the central complex, these fine-grained rocks are interbedded with sedimentary breccias and coarse-grained, gritty sandstones and lie unconformably on an irregular surface of Lewisian gneiss.

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At the top of the preserved Torridonian succession on Rum are fine-grained sandstones and siltstones, commonly with heavy-mineral concentrations, of the Sgorr Mhòr Sandstone Member, assigned to the Aultbea Formation. Outcrops are restricted to south and west Rum (Figure 2-64**;** Figure 2-65). Deposition was on a braid plain of a fluvial system.

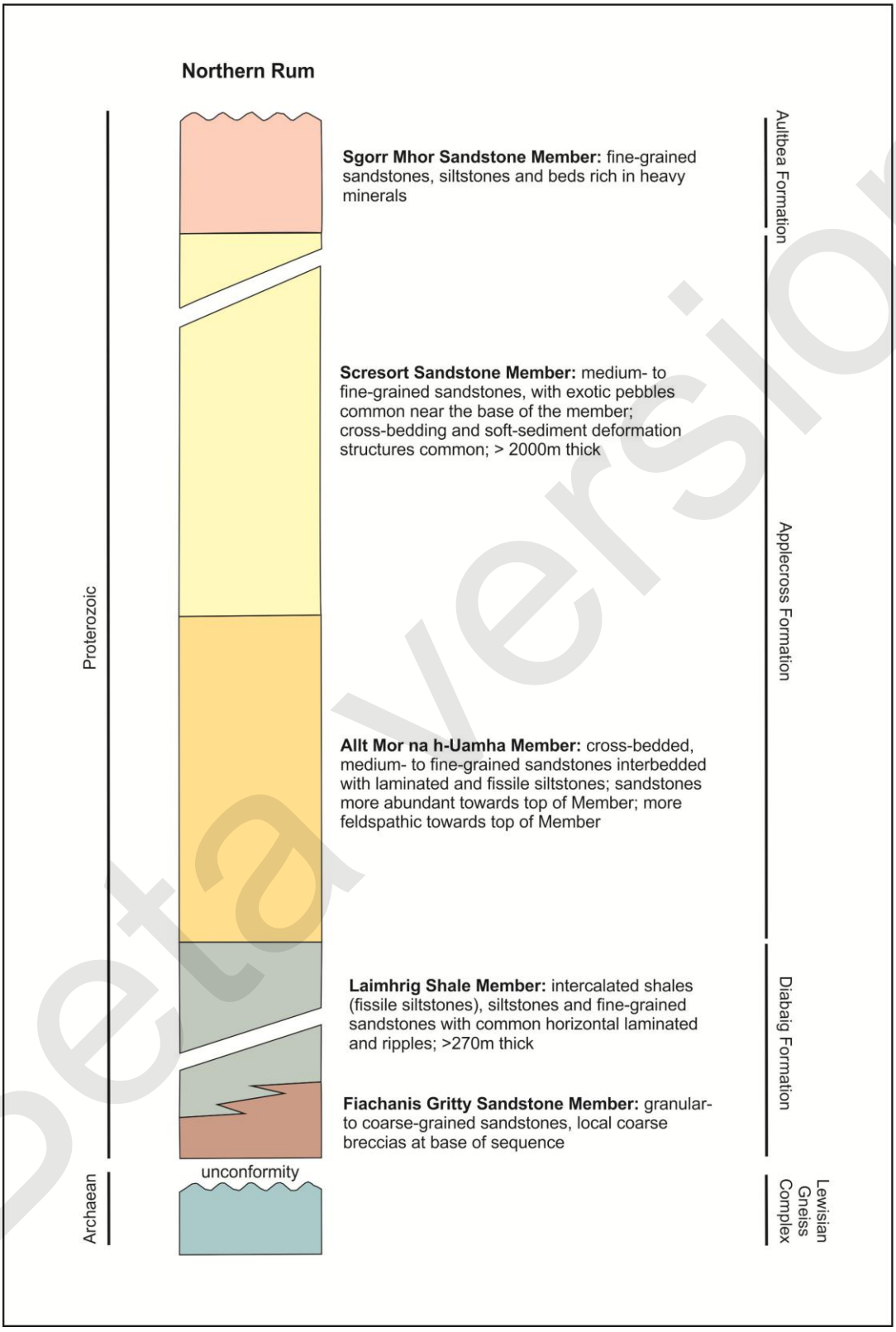


Figure 2-60: Lithostratigraphy of Torridonian Supergroup strata on Rum.

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Figure 2-61: Inclined Applecross Formation strata in north Rum.



Figure 2-62: Inclined Scresort Sandstone Member strata of the Applecross Formation on the north side of Loch Scresort, NE Rum.



Figure 2-63: Detail of inclined Scresort Sandstone Member strata of the Applecross Formation on the north side of Loch Scresort, NE Rum.

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Figure 2-64: Scresort Sandstone Member, Applecross Formation, SE Rum.

Revision

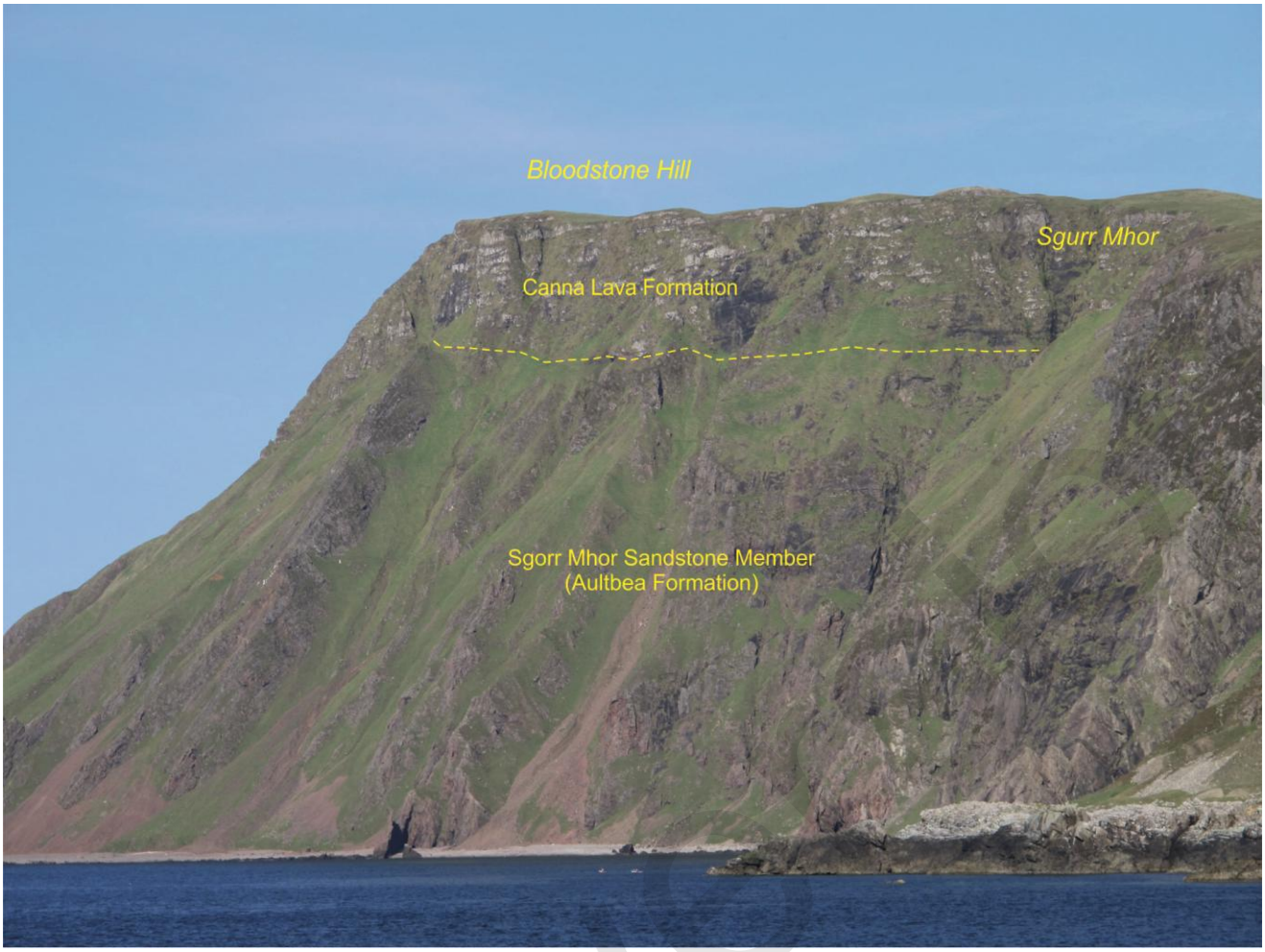


Figure 2-65: Sgòrr Mhòr Sandstone Member strata unconformably overlain by the Paleocene Canna Lava Formation at Bloodstone Hill, west Rum. Height of cliff is *ca*. 380 m.

2.3.5 Iona

The gneisses on Iona are overlain by the Iona Group, at least *ca*. 700 m thick, a sequence of sandstones with a basal conglomerate dominated by clasts of similar gneiss (Figure 2-66; Figure 2-67; Figure 2-68). Ripple lamination is a common feature, especially in the upper part of the sequence. To the east of Iona, skerries of the Caledonian Ross of Mull granite (see below) define the geographic limit of these strata. Detrital zircon U-Pb age data of 1490 ± 15 Ma give a maximum age. Various regional correlations have been suggested, including with the Torridon and Sleat groups, or even with the Late Proterozoic Colonsay Group, of 'Early Dalradian' age (McAteer *et al*. 2014).

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Figure 2-66: Basal conglomerate of the Iona Group, north Iona, with conspicuous clasts of basement gneiss. Pole *ca*. 1 m long.



Figure 2-67: Coarse grit(stone) of the Iona Group, dominated by fragments of gneiss, north Iona. Lens cap *ca*. 7 cm across.



Figure 2-68: Cleaved and faulted pelite (meta mudstone) of the Iona Group, NE Iona. Lens cap *ca.* 7 cm across.

2.4 Moine Supergroup

2.4.1 Introduction

A thick sequence of Late Proterozoic, medium- to fine-grained, clastic sediments, deposited in a shallow marine environment, has been lithified and regionally metamorphosed to form the pelitic, semipelitic and psammitic rocks of the Moine Supergroup ('Moine'). The metamorphosed equivalent of conglomerates is rare. In the Glenelg area on the Scottish Mainland, east of Skye, these Moine meta-sedimentary rocks unconformably overlie Lewisian gneisses. The date of sedimentation has not been precisely determined, although gneissose granite, dated at *ca.* 1083 Ma, cuts the Moine rocks (Strachan *et al.* 2024).

The Moine rocks have undergone polyphase deformation and regional metamorphism, reaching Amphibolite Facies over much of their outcrop. This metamorphic overprint, combined with intense ductile deformation, has largely destroyed original basin architecture and stratigraphic continuity. As a result, internal stratigraphy is difficult to reconstruct, and correlations rely heavily on lithological associations, structural position and geochronology. Sedimentary structures, such as cross bedding and grading, are locally preserved, but commonly are obliterated by the deformation and metamorphic events.

The depositional environment of the Moine Supergroup is interpreted as dominantly marine, in contrast to the continental Torridonian Supergroup (see above). Sedimentological and geochemical evidence suggests deposition on a broad continental shelf-to-slope system, with sediment supplied from the Laurentian craton.

Regional structural and sedimentological analysis indicates correlation between the Moine rocks and the sequences of Torridonian and Dalradian strata of the Inner Hebrides and adjacent Scottish Mainland (Figure 2-69; Figure 2-70) (Krabbendam *et al.* 2021). At its simplest, the Moine Supergroup is interpreted

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as recording marine sedimentation in a deeper, more distal basin, possibly located outboard of the Torridonian basins along the Laurentian margin.

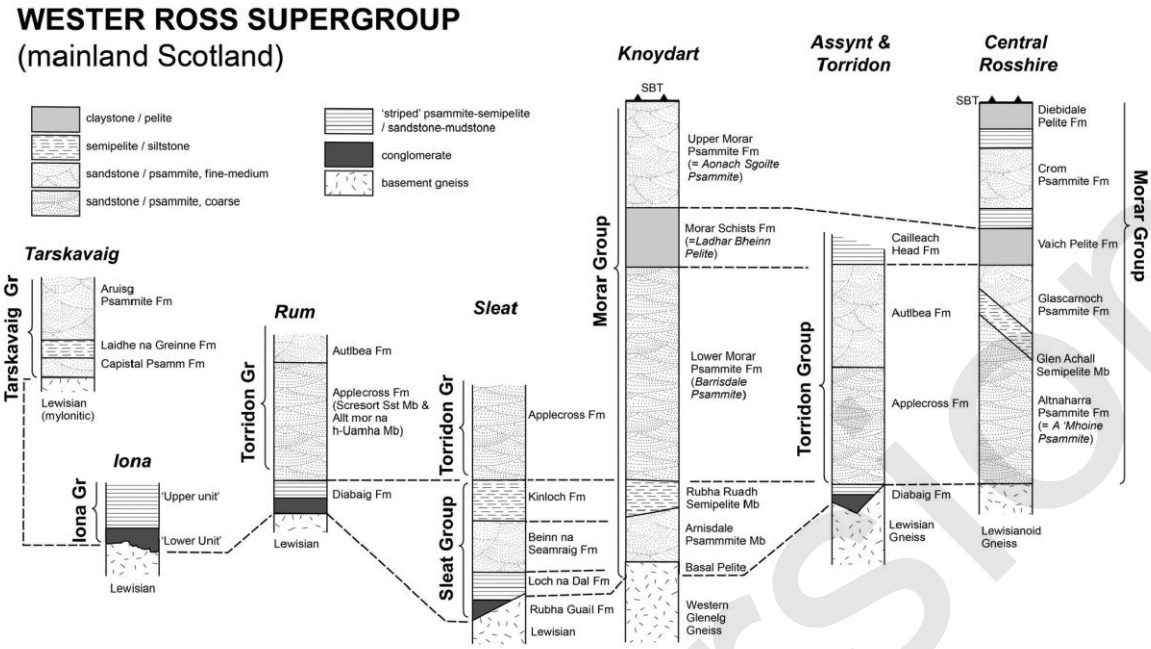


Figure 2-69: Wester Ross Supergroup (Skye, Iona, Rum) correlation. [Figure reproduced with permission from the British Geological Survey © UKRI 2025 All Rights Reserved. Source Krabbendam *et al.* 2021. DOI https://doi.org/10.1144/jgs2021-054. Permit Number CP25/041].

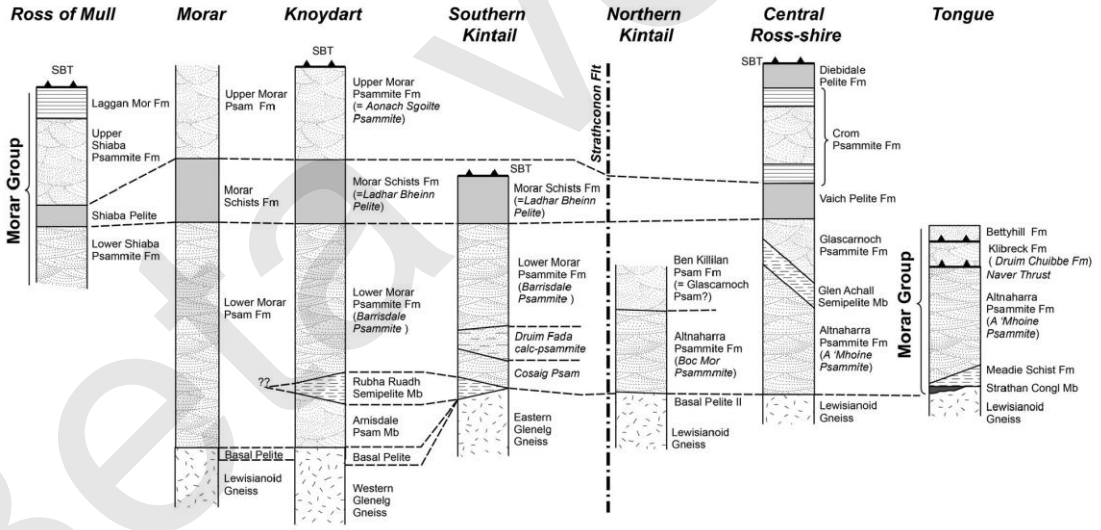


Fig. 5. Stratigraphic correlation chart of the Torridon–Morar groups – Wester Ross Supergroup. References to columns: *Tarskavaig*: Cheeney and Matthews (1965); *Iona*: Stewart (2002); McAteer *et al.* (2014); *Rum*: Stewart (2002); *Sleat*: Stewart (1969, 2002). *Assynt & Torridon*: Stewart (1969, 2002); *Ross of Mull*: Holdsworth *et al.* (1987) and this paper. *Morar*: Johnstone *et al.* (1969); Powell (1974); *Knoydart*: Ramsay and Spring (1962); Krabbendam *et al.* (2014); *Southern Kintail*: Tanner (1965); Krabbendam *et al.* (2014, 2018); *Northern Kintail*: May *et al.* (1993). *Central Ross-shire*: Bonsor *et al.* (2010, 2012); *Tongue*: Strachan and Holdsworth (1988). Alternative or older names in italics.

Figure 2-70: Wester Ross Supergroup (Ross of Mull, Morar) correlation. [Figure reproduced with permission from the British Geological Survey © UKRI 2025 All Rights Reserved. Source Krabbendam *et al.* 2021. DOI https://doi.org/10.1144/jgs2021-054. Permit Number CP25/041].

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2.4.2 Skye

Psammitic, semi-pelitic and pelitic rocks of the thrust-bound Tarskavaig Group crop out between the Kishorn and Moine thrust planes in Sleat, SE Skye (Figure 2-71). They are transitional in character between the weakly metamorphosed Torridonian rocks in the Kishorn Thrust Sheet to the west and the more intensely metamorphosed and deformed rocks of the Moine Supergroup that overlie the Moine Thrust to the east.

Significant synforms and antiforms are recognised within the thrust sheet (Figure 2-71; Figure 2-72Figure 2-72; Figure 2-74; Figure 2-75), and way-up criteria, such as cross stratification and grading, are preserved, enabling stratigraphic sequences to be defined, albeit poorly (Figure 2-76). Well-developed mylonites occur at the margin of the thrust sheet (Figure 2-77).

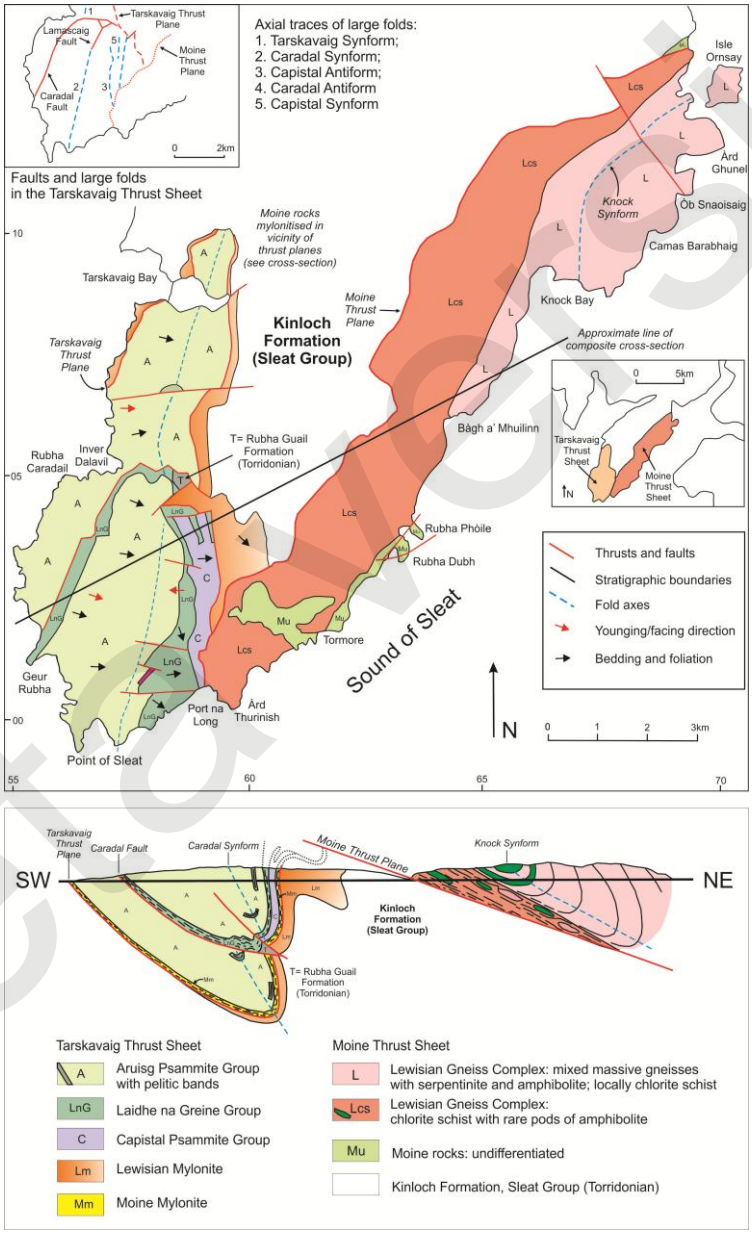


Figure 2-71: Simplified geological map and composite cross-section illustrating the main lithological and tectonic components of the Tarskavaig and Moine thrust sheets in the southern part of Sleat, SE Skye (after Cheeney & Matthews 1965).

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Figure 2-72: Tarskavaig Group semi-pelites, Point of Sleat.



Figure 2-73: Tarskavaig Group semi-pelites, Point of Sleat, Skye. Pole *ca.* 1 m long



Figure 2-74: Tarskavaig Group psammites and pelites, Camas Daraich, south Sleat, Skye. Pole *ca.* 1 m long.

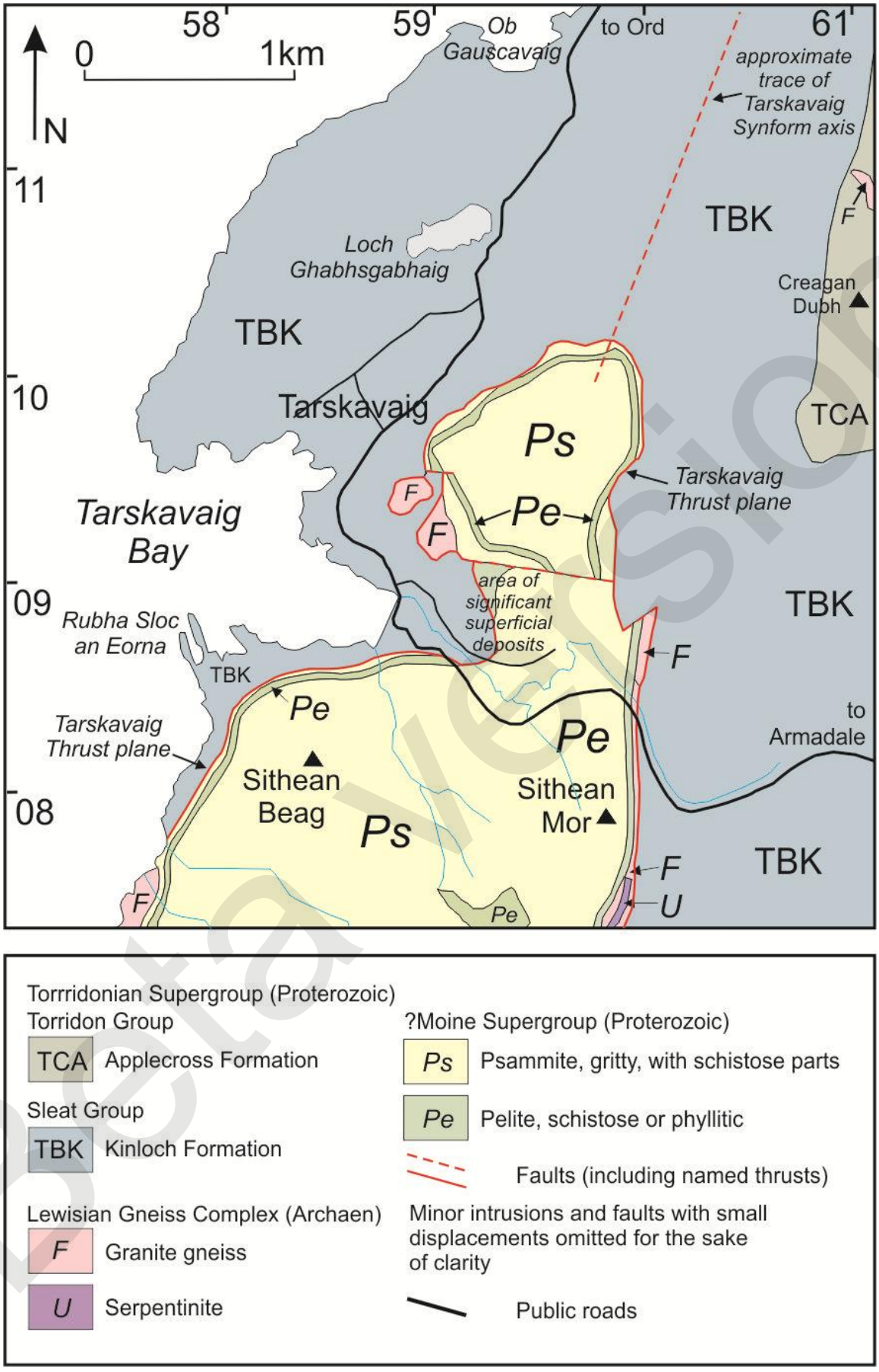


Figure 2-75: Simplified geological map of the Tarskavaig area, Sleat, SE Skye.

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Figure 2-76: Inverted cross-stratification within psammites, west of summit of Sìthean Mòr, Tarskavaig, Sleat, SE Skye. Coin *ca.* 24 mm across.



Figure 2-77: Mylonite formed from extreme ductile deformation of Moine Supergroup psammite west of the summit of Sìthean Mòr, Tarskavaig, Sleat, SE Skye. Coin *ca.* 24 mm across.

2.4.3 Ardnamurchan and Morvern

Mildly metamorphosed pebbly sandstones, sandstones and silty sandstones of the Morar Group of the Moine Supergroup are present in and around the Ardnamurchan Central Complex (Chapter 9), for example where they are intruded by Paleocene cone-sheets along the south coast at Kilchoan (Figure 2-78). They also underlie the Paleocene lavas and Mesozoic rocks on Ben Hiant (Figure 2-79; Figure 2-80) and on (the) Morvern (peninsula) (Figure 2-81). Higher grade psammitic rocks with granite veining, belonging to the Glenfinnan Group, underlie and crop out along the eastern edge of the lava pile on Morvern.



Figure 2-78: Moine psammites intruded by Paleocene cone-sheets, Kilchoan shore, Ardnamurchan. Main cone-sheet is *ca.* 2 m thick.



Figure 2-79: Morar Group (Moine Supergroup) psammites, east side of Ben Hiant, Ardnamurchan. Pole *ca.* 1 m long.

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Figure 2-80: Detail of Morar Group (Moine Supergroup) psammites, east side of Ben Hiant, Ardnamurchan. Pole *ca*. 1 m long.



Figure 2-81: Paleocene lavas overlying Moine Supergroup strata, north side of Morvern. View towards south from Ben Hiant, Ardnamurchan.

2.4.4 Mull

Rocks of the Glenfinnan Group occur around the margins of the Mull Central Complex (Chapter 9), for example in the core of the Craignure Anticline and beneath the Mesozoic rocks on the coast south of Gribun (Figure 2-70). Screens of Moine rocks occur between Paleocene inclined sheets and other minor intrusions in eastern Mull. Outside of the Mull Central Complex, fragments of Moine lithologies, including megablocks up to 100 m across, are common in ultra coarse units interpreted as vent infills, and in other volcaniclastic rocks (Bailey *et al*. 1924).

On the Ross of Mull, Moine rocks crop out SW of the Loch Assapol Fault, where they are intruded by the Late Caledonian Ross of Mull Pluton (Figure 2-82; Figure 2-83). Psammites and pelites dominate, together with metacarbonates, and are intruded by thick basaltic sills, now boudinaged garnet amphibolites (Figure 2-84; Figure 2-85; Figure 2-86; Figure 2-87). Multiple generations of fold events are recognised,

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including early, near-isoclinal folds, subsequently refolded in more open folds (Figure 2-88; Figure 2-89; Figure 2-90; Figure 2-91). Mylonites are present and are responsible for unknown displacements within the sequence (Figure 2-92).

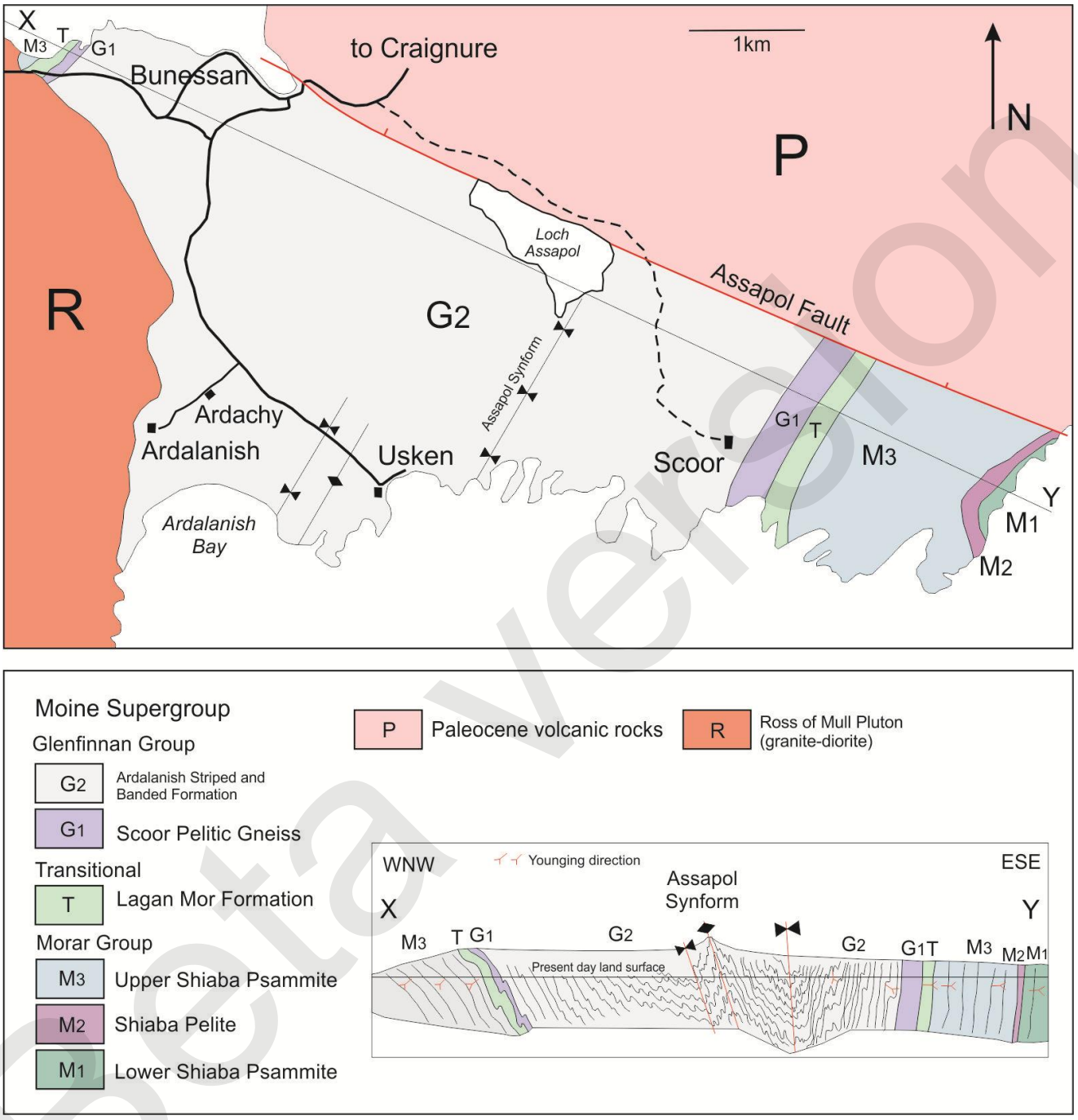


Figure 2-82: Distribution of the subdivisions of the Moine Supergroup sequence, Ross of Mull, SW Mull (after Holdsworth *et al.* 1987).

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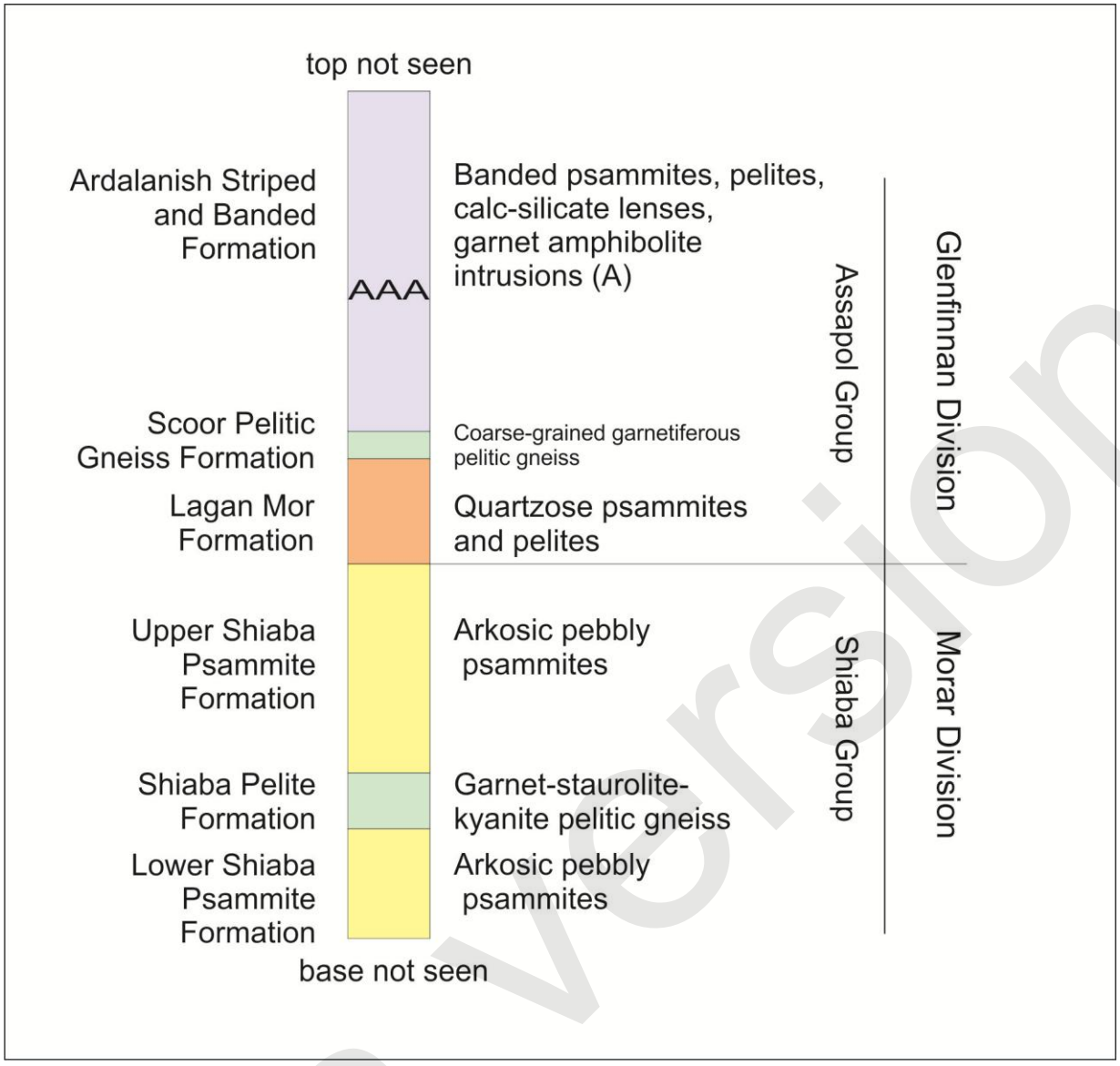


Figure 2-83: Lithologies of the subdivisions of the Moine Supergroup sequence, Ross of Mull, SW Mull (after Holdsworth *et al*. 1987).

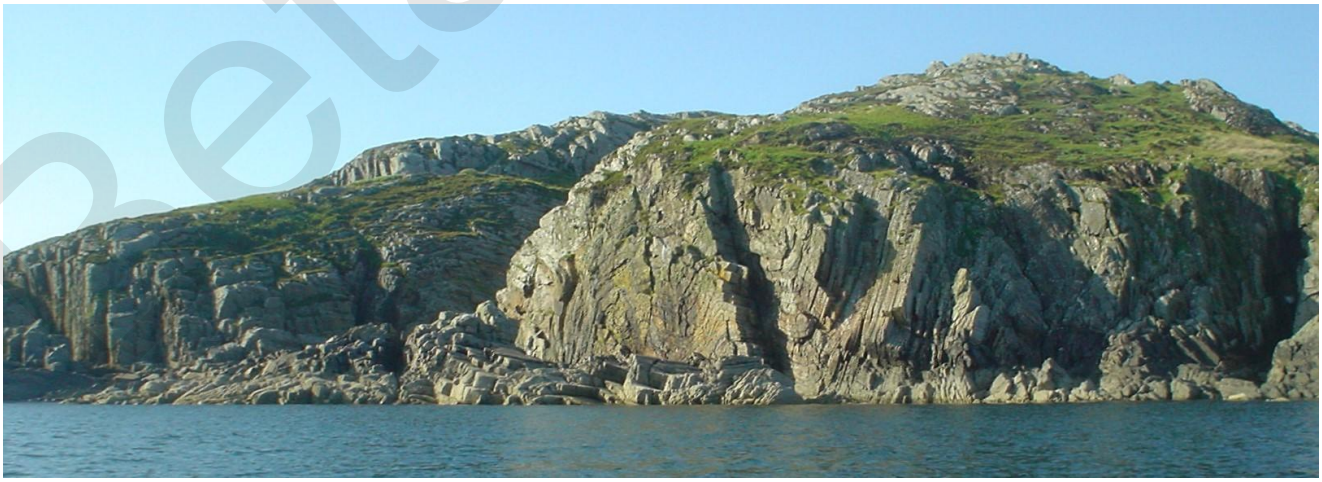


Figure 2-84: Folded Assapol Group psammites, east of Ardalanish Bay, south side of Ross of Mull, SW Mull.

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Figure 2-85: Folded Assapol Group psammites and amphibolites, east Ardalanish Bay, south side of Ross of Mull, SW Mull.



Figure 2-86: Detail of folded and thrusted Assapol Group psammites and amphibolites, east Ardalanish Bay, south side of Ross of Mull, SW Mull.



Figure 2-87: Boudinaged garnet amphibolite sheet (A) within psammites (P), central Ardalanish Bay, SW Mull.

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Figure 2-88: Detail of first-generation folds within folded Assapol Group psammites, east of Ardalanish Bay, south side of Ross of Mull, SW Mull.



Figure 2-89: Folded Assapol Group meta-carbonate (limestone/marble/calc-silicate), central Ardalanish Bay, south side of Ross of Mull, SW Mull.



Figure 2-90: Folded Assapol Group meta-carbonate (limestone/marble/calc-silicate), central Ardalanish Bay, south side of Ross of Mull, SW Mull. Coin *ca*. 24 mm across.



Figure 2-91: Folded Assapol Group pelites and psammites, east side of Ardalanish Bay, south side of Ross of Mull, SW Mull, illustrating the layer thickness – fold wavelength relationship.

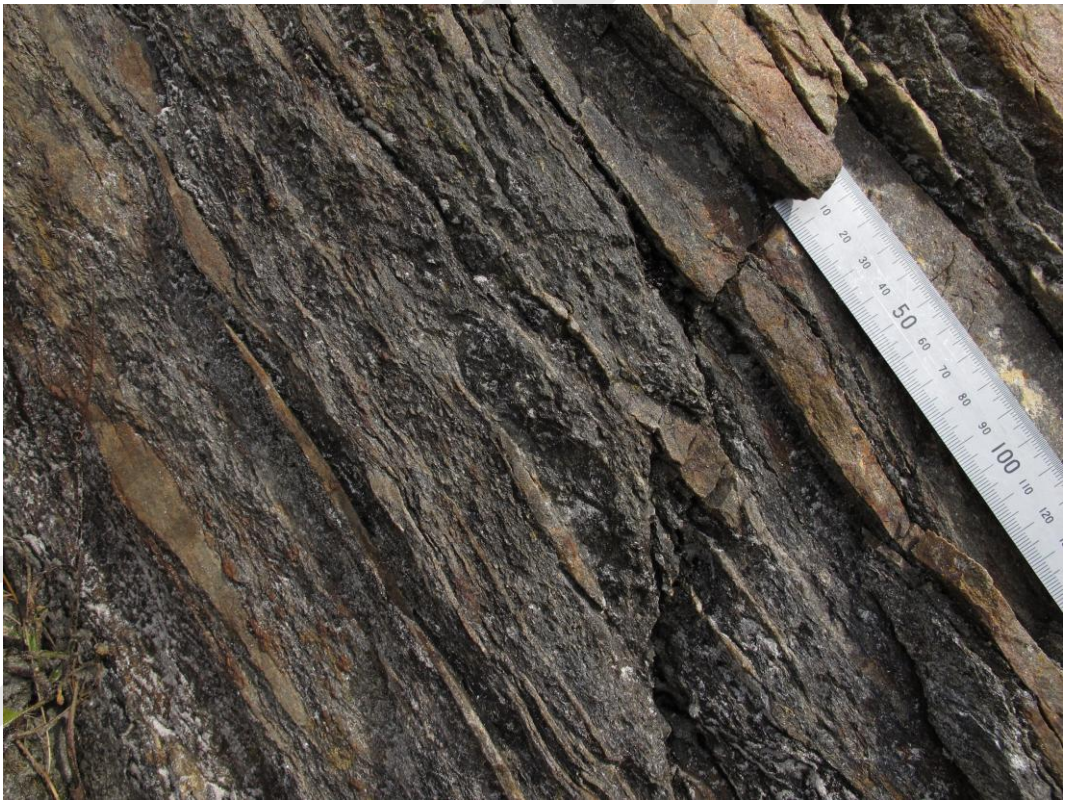


Figure 2-92: Mylonite, east Ardalanish Bay, SW Mull. Ruler scale (cm).

The sequences in north Ardmeanach - Gribun, west Mull, have a faulted contact with Paleocene basaltic lavas (Figure 2-93; Figure 2-94).



Figure 2-93: Folded Morar Group psammites and pelites, Gribun, west Mull, with faulted contact against horizontal Paleocene lavas.



Figure 2-94: Folded Morar Group psammites, Gribun, west Mull.

Numerous xenoliths and buchites of severely altered Moine rocks are present in the Paleocene Loch Scridain Sill-complex in SW Mull (Chapter 8) (Figure 2-95; Figure 2-96; Figure 2-97). The buchites are the product of extreme heating, up to and including partial melting, and reaction between fragments of pelite and the host basaltic magma of the minor intrusions. Varieties include anorthosite, mullite buchite and

cordierite buchite, the latter two comprising glass (now partially devitified) containing minerals crystallized at high temperatures. Mull sapphires, *not* of gem quality) occur in the mullite buchites.



Figure 2-95: Anorthosite buchite in a Paleocene basaltic intrusion (Loch Scridain Sill-complex), Killunaig, south shore of Loch Scridain, SW Mull. Hammer *ca*. 40 cm long.



Figure 2-96: Mullite buchite in Paleocene basaltic intrusion (Loch Scridain Sill-complex), Killunaig, south shore of Loch Scridain, SW Mull. Lens cap *ca*. 7 cm across.



Figure 2-97: Cordierite buchite in Paleocene basaltic intrusion (Loch Scridain Sill-complex), Killunaig, south shore of Loch Scridain, SW Mull. Hammer *ca.* 40 cm long.

2.5 Dalradian Supergroup

2.5.1 Introduction

Rocks belonging to the Late Proterozoic to Early Palaeozoic Dalradian Supergroup ('Dalradian') occupy much of the ground between the Great Glen Fault and the Highland Boundary Fault, but only on Arran are they a major part of the country-rocks to Paleocene intrusions.

In contrast to the lithological uniformity of the Torridonian and Moine supergroups (see above), the Dalradian is characterised by marked lithological and facies diversity. The succession is dominated by psammites, semipelites and pelites, but also contains substantial volumes of carbonate rocks, quartzites, graphitic schists and, locally, metavolcanic units. This diversity reflects deposition in a range of sedimentary environments and allows a more detailed stratigraphic subdivision than is possible within the Moine Supergroup.

The Dalradian Supergroup is conventionally subdivided into, in ascending order, the Grampian, Appin, Argyll and Southern Highland groups, representing a broadly upward-deepening and then shallowing succession. Although tectonically disrupted, this subdivision retains a depositional significance, unlike some subdivisions within the Moine Supergroup. The sequence records the evolution of a marine sedimentary basin system, ranging from shallow-marine shelf environments to deeper-water slope and basinal settings. The Grampian Group is dominated by siliciclastic rocks interpreted as shallow-marine to shelf deposits. The overlying Appin Group introduces abundant carbonates, indicating periods of reduced clastic input and stable shallow-marine platform conditions.

The Argyll Group records increased environmental complexity, including deeper-water facies, local basin restriction and episodes of volcanism. The Southern Highland Group is dominated by turbiditic and fine-

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grained siliciclastic deposits, interpreted as deep-water slope or basin-floor sediments, reflecting progressive basin deepening and increased tectonic instability.

(Meta)volcanic rocks occur within the Argyll Group and provide strong evidence for active extensional tectonics during Dalradian deposition and are interpreted as products of continental rifting or back-arc extension. This volcanism distinguishes the Dalradian basin from the Moine and aligns it more closely with large Late Proterozoic rift-related basin systems recognised elsewhere along Laurentia. The volcanic units also provide valuable geochronological constraints, confirming Dalradian deposition firmly within the Late Proterozoic.

Provenance studies indicate that Dalradian sediments were derived largely from Archaean and Early Proterozoic continental crust, consistent with erosion of the Laurentian craton. However, compared with the Torridonian and the Moine, the Dalradian sequence shows greater evidence of sedimentary recycling and more complex sediment-routing systems. The presence of mature quartzites, carbonates and fine-grained pelites suggests longer transport distances and more stable depositional environments, particularly during Appin Group times.

The Dalradian Supergroup has undergone regional metamorphism, typically reaching Greenschist to Amphibolite Facies, and intense polyphase deformation during the Caledonian orogeny, particularly the so-called Grampian Event. Folds, cleavage development and thrusts are pervasive, although primary sedimentary features are locally preserved, especially in lower-strain areas. However, metamorphism within the Dalradian is generally less intense and more variable than in the Moine, allowing clearer reconstruction of depositional environments and stratigraphic relationships.

The Dalradian Supergroup is an intermediate ‘element’ between the Torridonian and Moine supergroups, both geographically and tectonically. Like the Moine, the Dalradian represents marine sedimentation, but unlike the Moine it preserves clear evidence of basin evolution, facies transitions and volcanic activity. It is structurally separated from the Torridonian by major Caledonian structures, and there is no stratigraphic continuity between the two. However, the Dalradian shares with the Torridonian a broadly Late Proterozoic age and a Laurentian provenance, suggesting broadly contemporaneous sedimentation in different depositional domains.

The Dalradian Supergroup is better constrained chronologically than the Moine. Radiometric dating of metavolcanic rocks and detrital zircons places deposition from the early Late Proterozoic into the earliest Cambrian (Strachan *et al*. 2024). This long duration reflects prolonged basin development rather than a single depositional episode.

2.5.2 Mull

Phyllitic to slaty semi-pelites and black meta-limestones belonging to the Appin Group (possibly the Blair Atholl Subgroup) of the Dalradian Supergroup form the core of the Loch Don Anticline in SE Mull. They are separated from Moine rocks on Mull by a continuation of the Great Glen Fault.

2.5.3 Arran

Low-grade, regionally metamorphosed, gritty and pebbly (meta-) sandstone, with subsidiary (slaty meta) siltstone and (meta-) mudstone, of the uppermost Southern Highland Group dominate much of the pre-Paleocene rocks of north Arran. Two units are recognized: the older Loch Ranza Slates and the younger

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North Sannox Grits (Figure 2-98). Within the latter, intervals of black slates and green slates are distinguished. Metamorphism peaked in the Upper Cambrian at *ca*. 520 Ma at a relatively low pressure and temperature (2-4 kbar and 300-400°C) in the Greenschist Facies. They were displaced and folded during the emplacement of the Paleocene North Arran Granite Pluton (Chapter 9) and are overlain by, or are in faulted contact with, younger rocks to the east. The original strata are interpreted as a sequence of turbidite deposits, and many of the original sedimentary structures are still preserved, aiding interpretation of Paleocene and earlier folding events (Figure 2-99; Figure 2-100; Figure 2-101; Figure 2-102; Figure 2-103).

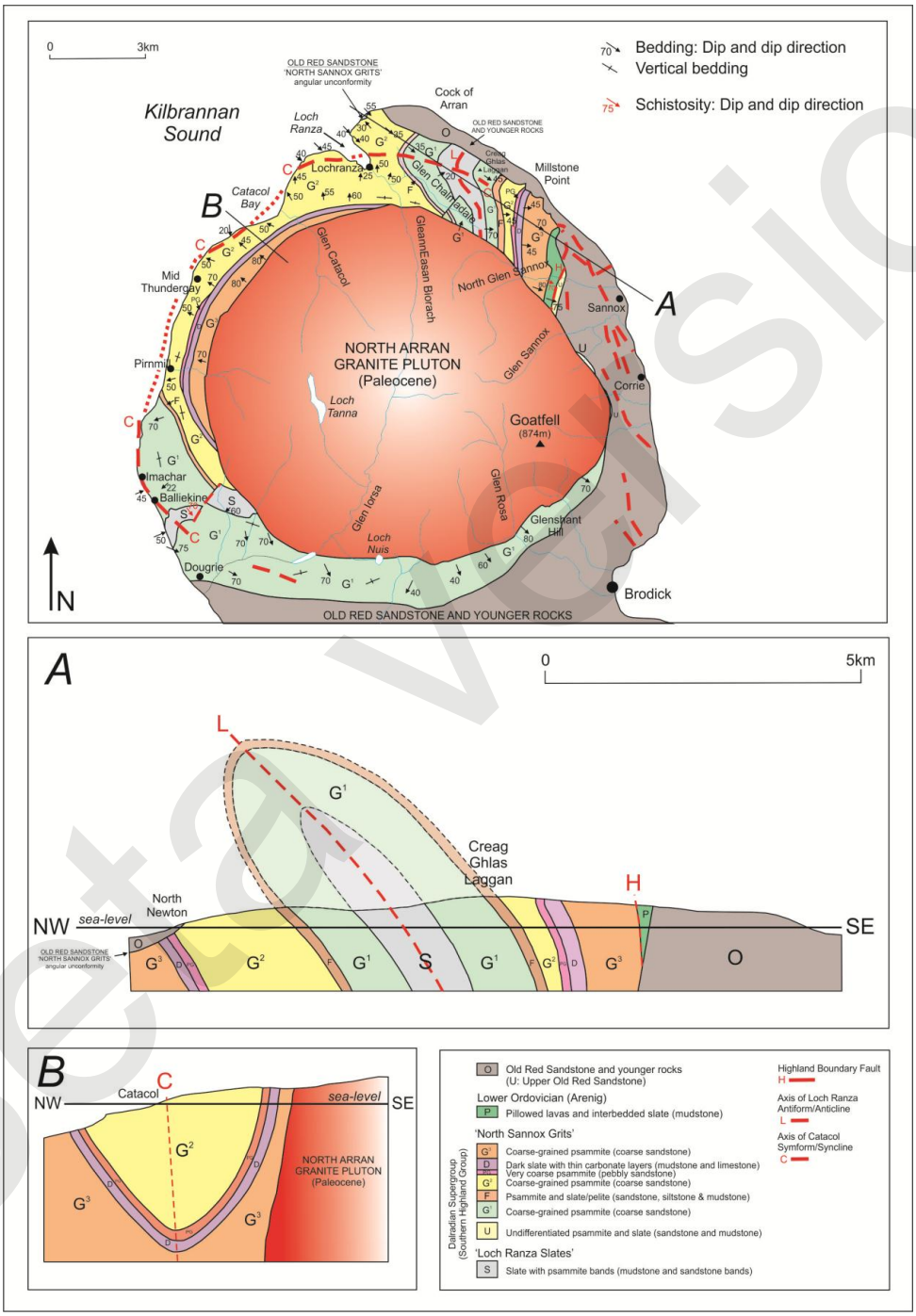


Figure 2-98: Map and cross-sections illustrating the distribution of Dalradian Supergroup strata in north Arran (after various sources).

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Figure 2-99: Semi-pelites at Craw, between Catacol and Lennimore, NW Arran. Pole *ca.* 1 m long.



Figure 2-100: Semi-pelites with a crenulation cleavage, south of Imachar, NW Arran. Pole *ca.* 1 m long.

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Figure 2-101: Semi-pelites with a crenulation cleavage, south of Imachar, NW Arran. Pole *ca.* 1 m long.



Figure 2-102: Pelites at Rubha Airigh Bheirg, NW Arran. Coin *ca*. 24 mm across.



Figure 2-103: Coarse 'grits' (psammite), shore at High Whitefarland, NW Arran. Coin *ca*. 24 mm across.

2.6 Lower Palaeozoic

2.6.1 Introduction

The youngest group of rocks that are part of the Hebridean Terrane are of Cambrian and Ordovician (Cambro-Ordovician) age (Goodenough *et al*. 2024). These strata unconformably overlie rocks of the Lewisian Gneiss Complex and the Torridonian Supergroup and were also involved in the Lower Palaeozoic (Caledonian) orogenic events of NW Scotland. On Skye, these rocks occur as a foreland sequence around Ord, on the west side of Sleat (all units except the Strath Suardal Formation), and as units within the Moine Thrust Zone on Sleat and in Strath. A very small outcrop of marble in Camasunary Bay may also be attributed to the Cambro-Ordovician sequence.

The outcrops of Cambro-Ordovician rocks, together with strata of the Torridonian Kinloch and Applecross formations, occur within a structure referred to as the Ord Window (Figure 2-104). This structure, a stratigraphical outlier, is surrounded by older rocks; but it is a structural inlier in the sense that it has been interpreted as an area of the foreland that has been exposed by erosion through overlying thrust sheets of the Moine Thrust Zone (MTZ). The inlier is characterised by folded, steeply dipping, fault-bound slices. A number of stratigraphic-structural interpretations have been proposed. Clough (in Peach *et al*. 1907) envisaged the Ord structure as a tectonic window in the core of a relatively open antiform, in which essentially right-way-up sequences are separated by two thrusts within the lower part of the MTZ. Bailey (1939, 1955) re-interpreted Clough's work and suggested that the inlier consists of a pair of large recumbent folds, with inversion of strata. The two thrusts were interpreted as branches of the Kishorn Thrust on the lower limb of the recumbent Lochalsh Syncline and the lowest structures in this part of the MTZ. The core of the inlier could therefore be regarded as part of the foreland. Potts (1982) envisaged the rocks of the inlier as part of a recumbent fold, analogous to, but at a lower structural level than, the Lochalsh Syncline, and re-interpreted some of the thrusts as normal stratigraphical junctions. To date, there is no consensus on the preferred/correct model and there is considerable scope for further interpretation (Figure 2-105). A lack of key exposures of some contacts is a significant issue in this regard.

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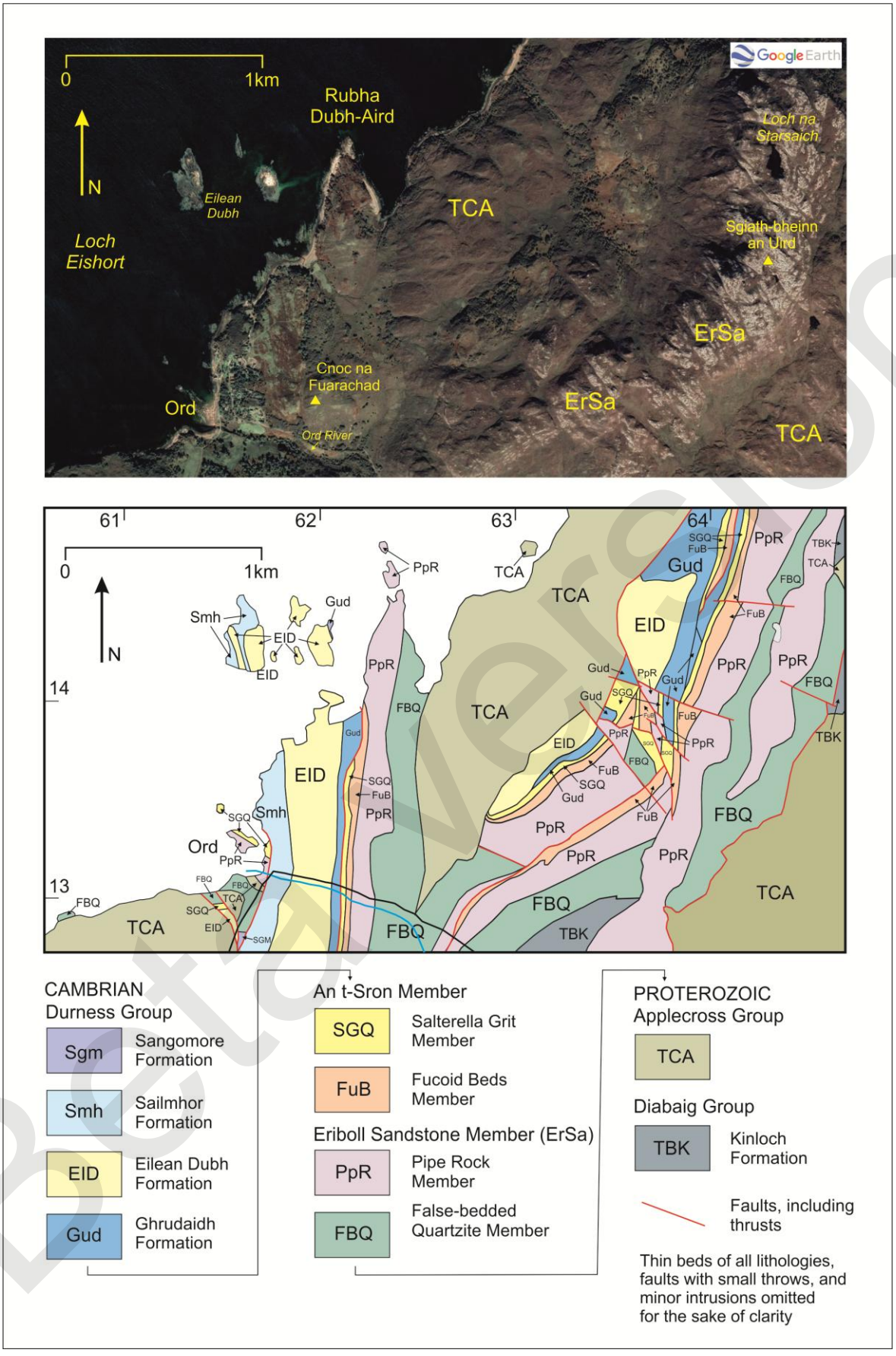
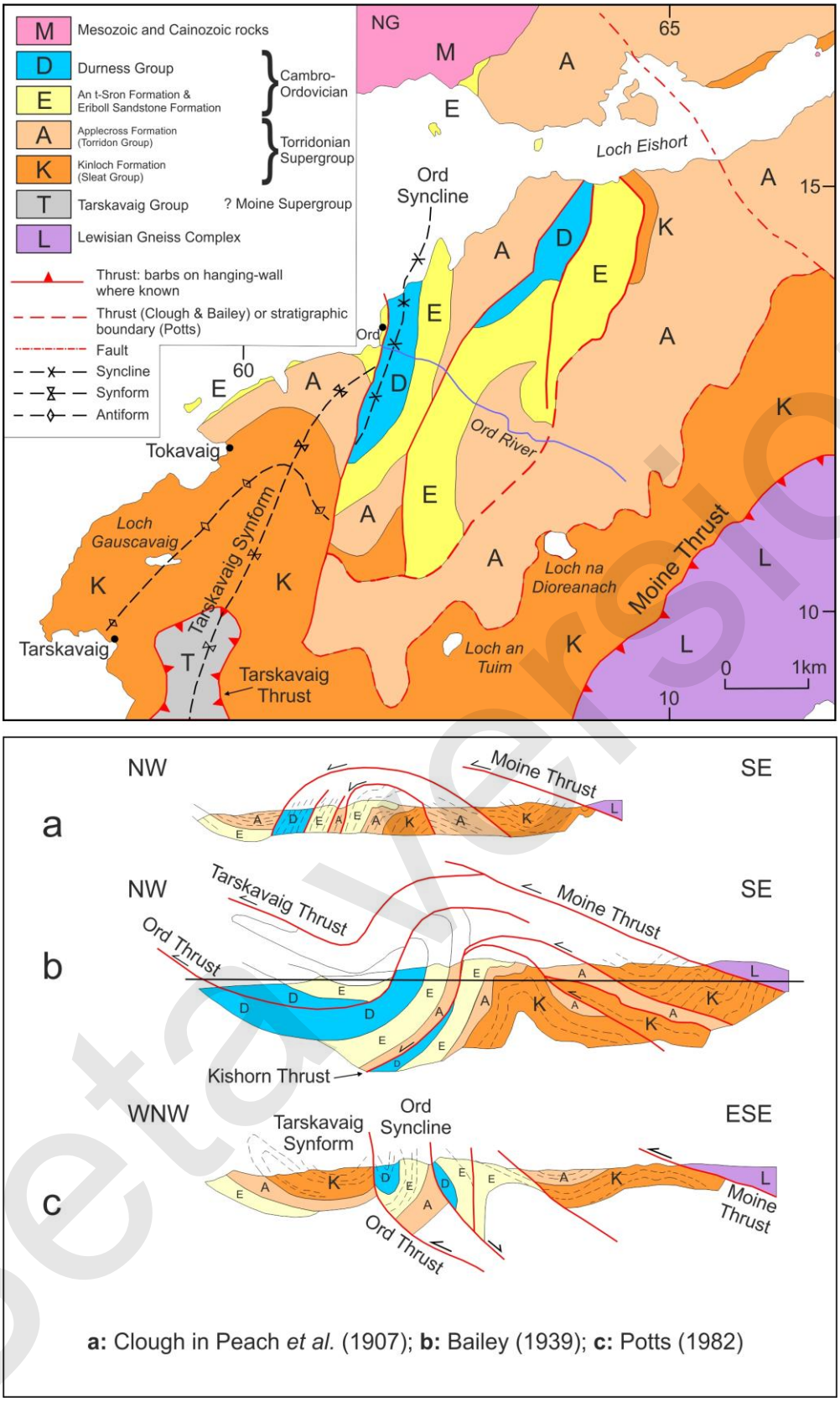


Figure 2-104: Simplified geological map and annotated Google Earth® image of the area around Ord.

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a: Clough in Peach *et al.* (1907); **b:** Bailey (1939); **c:** Potts (1982)

Figure 2-105: Simplified geological map and differing cross-section interpretations illustrating the main lithological and tectonic components of the Tarskavaig and Moine thrust sheets in the central part of Sleat between Ord and Tarskavaig (after Emeleus & Bell 2005).

At its simplest, the Cambro-Ordovician sequence was deposited within the inner part of a shelf in relatively shallow water during a marine transgression on the southern passive margin of Laurentia,

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bordered to the south by the Iapetus Ocean (e.g. Prave *et al.* 2024) (Figure 2-106). The palaeo-latitude was just south of the equator, and the climate was tropical. The Eriboll Sandstone Formation and the An t-Sron Formation comprise various clastic units, whereas the overlying Durness Group are marine carbonates (dolostones) formed due to low sediment run-off from the continental interior.

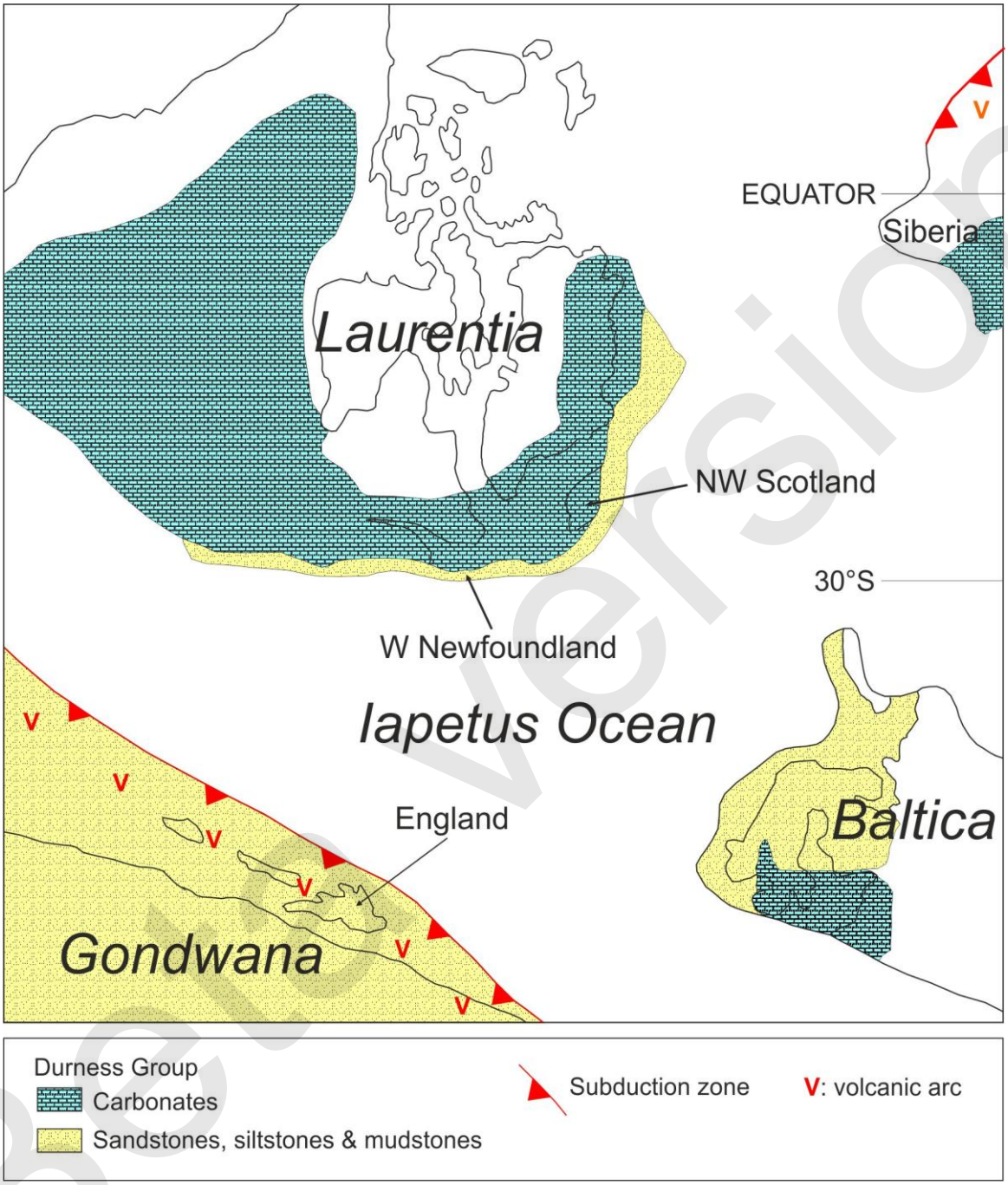


Figure 2-106: Palaeogeographic interpretation illustrating depositional facies during Lower Cambrian times (after McKerrow *et al.* 1991).

Cambrian sedimentation began with the deposition of the Ardvrek Group, a *ca.*150-200 m thick sequence dominated by siliciclastic sediments (Figure 2-107). The Eriboll (Sandstone) Formation, a basal unit of quartz arenites and minor conglomerates, comprises the False-bedded (or Basal) Quartzite Member, which sits unconformably on a 'basement' of either Lewisian gneiss or Torridonian strata, and consists of white to pale grey, coarse- to medium-grained quartz arenites, locally pebbly at the base. Bedding is typically thick and planar, with common trough and planar cross-stratification.

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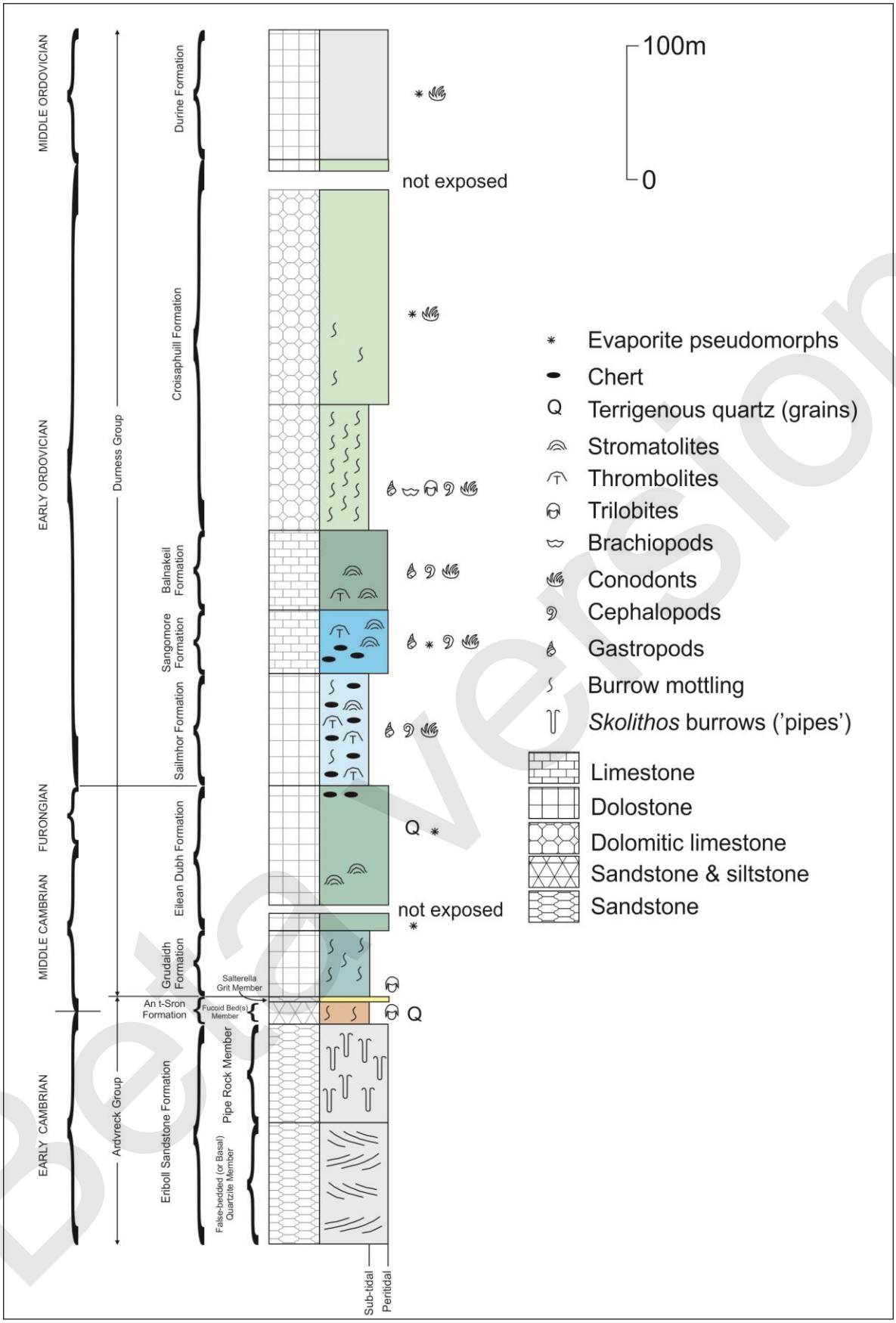


Figure 2-107: Cambro-Ordovician lithostratigraphy (after various sources).

The maturity of these sandstones reflects derivation from a low-relief Laurentian cratonic hinterland to the NW and extensive sediment reworking. The basal contact is commonly sharp and locally erosional,

Beta version

suggesting a marine transgression across a weathered basement surface. Depositional environments are interpreted as high-energy nearshore and shoreface systems, including tidal bars and sandy shoals.

Overlying the False-bedded Quartzite Member is the distinctive Pipe Rock Member, which consists of fine- to medium-grained quartz arenites characterized by abundant vertical, sand-filled burrows, customarily known as 'pipes'. These structures, a few millimetres up to several centimetres in diameter, are identified as *Skolithos-type* trace fossils, produced by suspension-feeding organisms in a high-energy shallow-marine setting. The density and vertical orientation of the burrows indicate well-oxygenated, shifting sandy substrates.

The overlying An t-Sron Formation comprises two members, both predominantly clastic: the lower Fucoid Bed(s) Member and the upper Salterella Grit Member. Deposition was tidal and storm influenced on a shallow marine shelf (Prave *et al.* 2024).

The pale, orange-brown Fucoid Beds Member, up to 20 m thick, comprises rippled and cross-stratified calcareous siltstones and sandstones, with distinctive but rare olenellid trilobites and echinoderms. The name derives from the mistaken identification of the trace fossil markings (ichnofossils) of seaweed, or 'fucoids' (Peach *et al.* 1907). Modern interpretation is that the fucoids are the trace-fossil burrows of *Planolites,* creatures akin to trilobites or worms.

The overlying Salterella Grit Member, typically less than 10 m thick, is composed predominantly of fine- to coarse-grained quartz arenites with rounded and frosted grains of quartz, suggestive of aeolian transport at some stage prior to deposition. Bed forms include planar and (trough) cross-stratification, with common rippled surfaces. Its name derives from conical, millimetre-sized Salterellids (marine organisms with tube-like shells). The presence of *Skolithos* trace-fossils can, in places, make distinction from the Pipe Rock Member difficult.

Ordovician sedimentation is represented principally by the Durness Group, a thick, up to 1200 m, carbonate succession dominated by limestones and dolostones. These strata infer deposition on a warm, low-latitude platform, with minimal siliciclastic input.

Lithologies include pale and dark massive and bedded limestones, dolomitic limestones and dolostones, together with locally developed evaporite units. The dominance of carbonate reflects a combination of low relief on the Laurentian hinterland, limited terrigenous sediment supply and favourable climatic conditions. Deposition of the Durness Group sediments was part of a much larger carbonate bank on the margin of the Laurentian craton. Fossil assemblages are more diverse than in the Cambrian, including brachiopods, gastropods, cephalopods and trilobites, allowing more refined biostratigraphic subdivisions. Faunal affinities clearly link the succession to other Ordovician carbonate platforms along the Laurentian margin. A wide variety of carbonate textures and bedforms are recognised (e.g. Prave *et al.* 2024 and references therein), including: cross-stratified grainstones, oolitic packstones and wackstones, and bioclastic wackstones, together with thin units with characteristics typical of evaporites, such as gypsum pseudomorphs. Replacive chert nodules, ranging from light to dark, some pale orange, are common. Stromatolites are a relatively common feature, as is bioturbation, the latter locally responsible for the near obliteration of primary depositional features.

Diagenetic processes, particularly dolomitisation, exerted a strong influence on the present character of the succession and most likely occurred soon after deposition, facilitated by warm temperatures and restricted circulation in the shallow-marine setting.

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Despite later deformation, these Cambro–Ordovician strata of the foreland preserve a relatively low-grade metamorphic overprint, retaining primary sedimentary textures and fossils. This preservation contrasts sharply with the higher-grade metamorphism recorded in adjacent allochthonous units.

2.6.2 Skye

The lower part of the Cambro-Ordovician succession crops out in a highly complex structure around Ord, on Sleat, SE Skye. At the base of the sequence, 'quartzites' – quartz-cemented quartz arenites - of the Eriboll Sandstone Formation (comprising the False-bedded Quartzite Member and the commonly bioturbated Pipe Rock Member), and the An t-Sron Formation are all Early Cambrian in age (Figure 2-107; Figure 2-108; Figure 2-109; Figure 2-110; Figure 2-111; Figure 2-112; Figure 2-113 ; Figure 2-114; Figure 2-115; Figure 2-116; Figure 2-117**)**. The An t-Sron Formation consists of the Fucoid Beds and Salterella Grit members. The Fucoid Beds consist mainly of dolomitic siltstones characterised by trace-fossil remains originally thought to resemble seaweed markings (see above) (Figure 2-118). The Salterella Grit Member comprises quartz arenites with remnants of the small gastropod *Salterella*. The overlying Ghrudaidh, Eilean Dubh and Sailmhor formations (Durness Group) range from mid Cambrian to earliest Ordovician in age and are best exposed in coastal sections; they consist of dolomitic limestones and dolostones that are commonly cherty (Figure 2-119; Figure 2-120; Figure 2-121).



Figure 2-108: The (Cambrian) quartzite ridge of Sgiath-bheinn an Uird (left) and Meall Dà-Bheinn - Sgiath-bheinn Chrosabhaig (right), Sleat, with the Scottish Mainland hills of Knoydart (centre) in the distance. View towards the east from Strathaird.



Figure 2-109: The (Cambrian) quartzite ridge of Sgiath-bheinn an Uird, Sleat, and the Scottish Mainland hills of Knoydart (right) in the distance. View towards the east from Strathaird.

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Figure 2-110: The (Cambrian) quartzite ridge of Sgiath-bheinn an Uird, Sleat. View towards the SE from Heaste, Strath.



Figure 2-111: White, fractured Eriboll Sandstone Formation, Sgiath-bheinn an Uird, Sleat, SE Skye, with glacial erratics of brown-orange Torridonian sandstone. Pole *ca*. 1 m long.



Figure 2-112: Near-vertical, stratified Eriboll Sandstone Formation, Sgiath-bheinn an Uird, Sleat, SE Skye.

Beta Version



Figure 2-113: Inclined Pipe Rock Member strata om the north side of the small bay opposite Eilean Gaineamhach an Arda. Pole *ca.* 1 m long.



Figure 2-114: Detail of bedding surface of inclined Pipe Rock Member strata on the north side of the small bay opposite Eilean Gaineamhach an Arda. Coin *ca.* 24 mm across.



Figure 2-115: Gritty False-bedded Quartzite Member of the Eriboll Sandstone Formation, NE of Tarskavaig, Sleat, SE Skye. Coin *ca*. 24 mm across.



Figure 2-116: False-bedded Quartzite Member of the Eriboll Sandstone Formation, NE of Tarskavaig, Sleat, SE Skye. Coin *ca*. 24 mm across.



Figure 2-117: Bedding surface of Pipe Rock Member of the Eriboll Sandstone Formation, north of Ord, Sleat, SE Skye. Hammer *ca.* 30 cm long.



Figure 2-118: Steeply-inclined, orange-weathering sandstones of the Fucoid Beds Member of the An t-Sròn Formation, north of Ord, Seat, SE Skye. Coin *ca.* 24 mm across.



Figure 2-119: Durness Group limestone with bedding-parallel chert stringers, north of Ord, Sleat, SE Skye. Pole *ca*. 1 m long.



Figure 2-120: Laminated and rippled calcareous mudstones of the Eilean Dubh Formation. Coin *ca*. 24 mm across.

Preview



Figure 2-121: Chert nodules within laminated calcareous mudstones of the Eilean Dubh Formation. Pole *ca.* 1 m long.

A thick, chert-bearing dolostone sequence crops out extensively between Broadford and Loch Slapin in Strath (Figure 2-122; Figure 2-123; Figure 2-124; Figure 2-125; Figure 2-126; Figure 2-127; Figure 2-128; Figure 2-129). It is separated from the Cambro-Ordovician outcrops of Sleat by several kilometres, with only small fault-bound outcrops of the Eriboll Sandstone Formation in the intervening ground. Gastropods, bivalves and sponges have been identified, for example near the outlet of Loch Kilchrist, and these dolostones are considered to be of Early Ordovician (Arenig) age.

However, the succession cannot be equated easily or directly with the upper part of the Durness Group elsewhere and hence is (locally) named the Strath Suardal Formation (Figure 2-122). These dolostones underlie overthrust Torridonian strata of the Kishorn Thrust Sheet and are intruded by igneous rocks of Paleocene age, including the Beinn an Dubhaich Granite, the Broadford Gabbro (Chapter 9) and numerous Paleocene dykes (Chapter 7). Near-to-isoclinal folds can be identified, although exposures of obvious closures are not common (Figure 2-130). Dolostones in contact with the granite and gabbro have been altered to a variety of calc-silicate skarns, including the well-known yellow and green decorative ‘Skye Marble’, which contains diopside, serpentine and brucite (Chapters 9 & 14).

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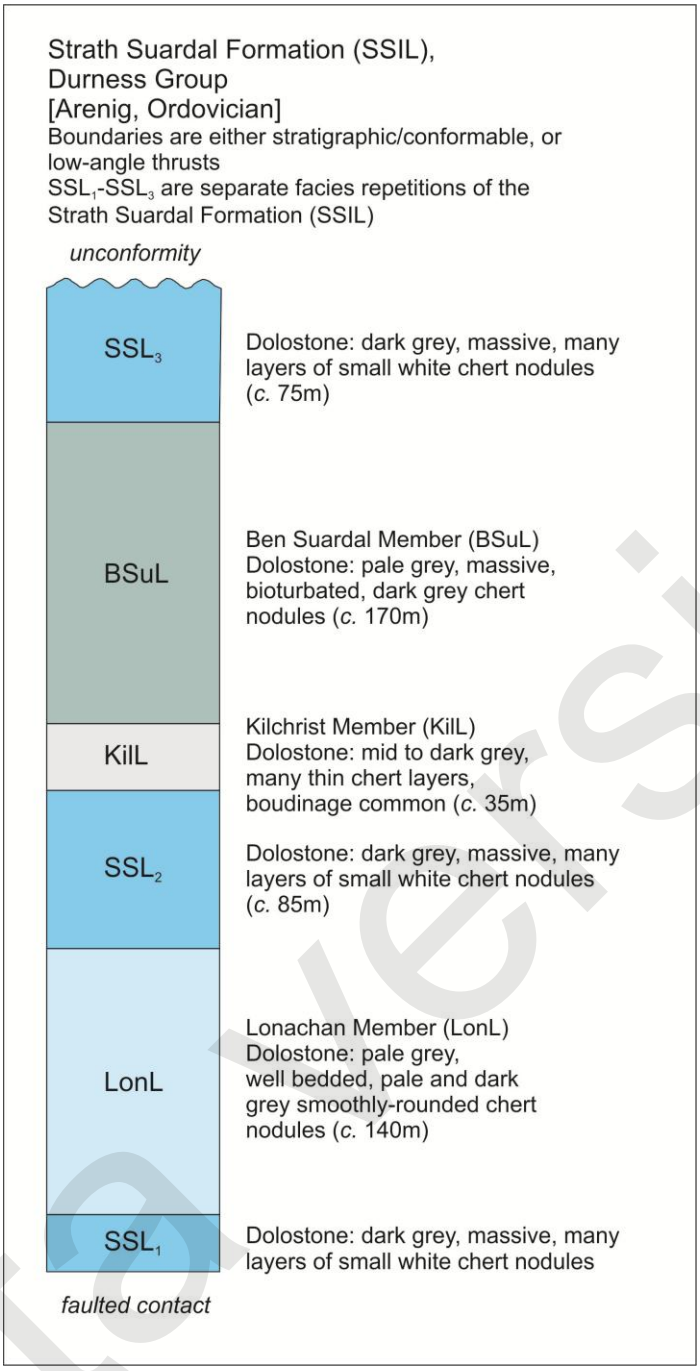


Figure 2-122: Strath Suardal Formation lithostratigraphic column (after BGS 2002).



Figure 2-123: Ben Suardal Member of the Strath Suardal Formation, Durness Group, dolostones forming the ridge of Ben Suardal, Strath, Skye.

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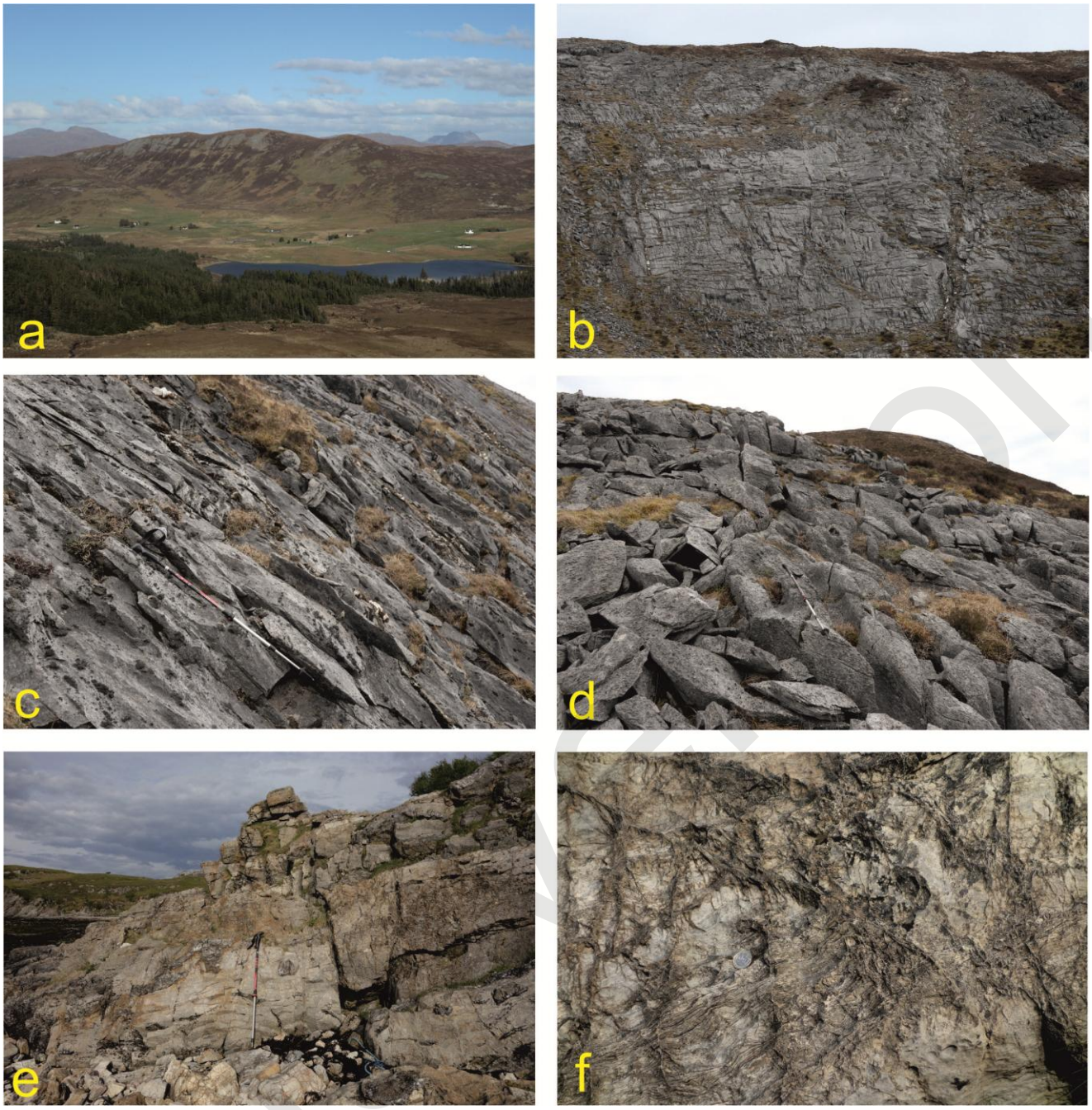


Figure 2-124: Durness Group strata: (a) Ben Suardal from Kilchrist, Strath; (b) steeply dipping Ben Suardal Member dolostones on the NW face of Ben Suardal, Strath; (c) detail of Ben Suardal Member dolostones with chert nodules, Ben Suardal, Strath; (d) detail of Ben Suardal Member dolostones with typical clint and gryke solution weathering, Ben Suardal, Strath; (e) with chert nodules on the south side of Camas Chathabhaig, Ord; and, (f) intensely veined calcareous mudstones of the Eilean Dubh Formation, Ord. Pole *ca.* 1 m long; coin *ca.* 24 mm across.

BGS



Figure 2-125: Dolostones of the Strath Suardal Formation, Durness Group, on the north side of the Allt nan Leac valley at Loch Slapin, Strath, Skye.



Figure 2-126: Dolostones of the Strath Suardal Formation, Durness Group, on the north side of the Allt nan Leac valley, Strath, Skye.

Preview



Figure 2-127: Chert nodules in dolostones of the Strath Suardal Formation, Durness Group, on the south side of the Allt nan Leac valley, Strath, Skye. Coin *ca*. 20 mm across.



Figure 2-128:Chert nodules in dolostones of the Strath Suardal Formation, Durness Group, on the south side of the Allt nan Leac valley, Strath, Skye. Pole *ca*. 1 m long.



Figure 2-129: Stringers of chert nodules in dolostones of the Strath Suardal Formation, Durness Group, on the south side of the Allt nan Leac valley, Strath, Skye. Pole *ca.* 1 m long



Figure 2-130: Folded Durness Dolostones, Allt na Garbhlain, Strath, Skye. Ruler scale.

Within Camasunary Bay there is a small outcrop of marble, originally attributed a Jurassic age (Peach *et al*. 1910) (Figure 2-131). In a mineralogical study of this rock, Wyatt (1952) identified two high-temperature calc-silicate minerals, spurrite and rankinite. A subsequent investigation by Beard & Drake (2007), identified melilite, another high-temperature calc-silicate mineral, together with wollastonite, vesuvianite, tilleyite, andradite-grossular garnet, monticellite and perovskite, all indicative of extremely high-grade thermal metamorphism, within the Sanidinite Facies and with a peak metamorphic temperature possibly in excess of 900°C at an assumed depth of no more than 1 km. Metamorphism was not isochemical and the rock is better described as a skarn. The identification of chert nodules and stringers, similar to those in Cambro-Ordovician Durness Group dolostones within the Moine Thrust Zone, together with the development of abundant calc-silicate minerals, is used by Beard & Drake (2007) to argue that the original rock was a dolostone with a more likely Cambro-Ordovician age. One inference of this interpretation is that the (not seen) contact between the metamorphosed dolostone and surrounding Torridonian strata is a thrust plane, with the latter structurally above the former, as is the case for the Kishorn Thrust Plane, which crops out NW of Bheinn Shurdail in Strath.



Figure 2-131: Metamorphosed dolostone (marble) in Camasunary Bay, interpreted to be part of the Durness Group, with a complex assemblage of high-temperature (calc-silicate) minerals. Pole *ca*. 1 m long.

2.6.3 Arran

A thickness of *ca.* 300 m of black mudstones and chloritised (spilitic) pillow lavas, together with rare beds of chert or tuff, is exposed in the North Glen Sannox River in NE Arran (Figure 2-132; Figure 2-133). Poorly preserved brachiopod remains obtained from the mudstone indicate an Arenig age for these deposits. The sequence occurs adjacent to Dalradian Supergroup meta-sandstones and is cut by sheets of altered dolerite and gabbro. It forms part of the Highland Border Complex, which crops out along the Highland Boundary Fault between Arran and Stonehaven (Stephenson & Gould 1995). Prave *et al.* (2024) assign these rocks to the so-called Trossachs Group, close to the top of the Dalradian Supergroup.

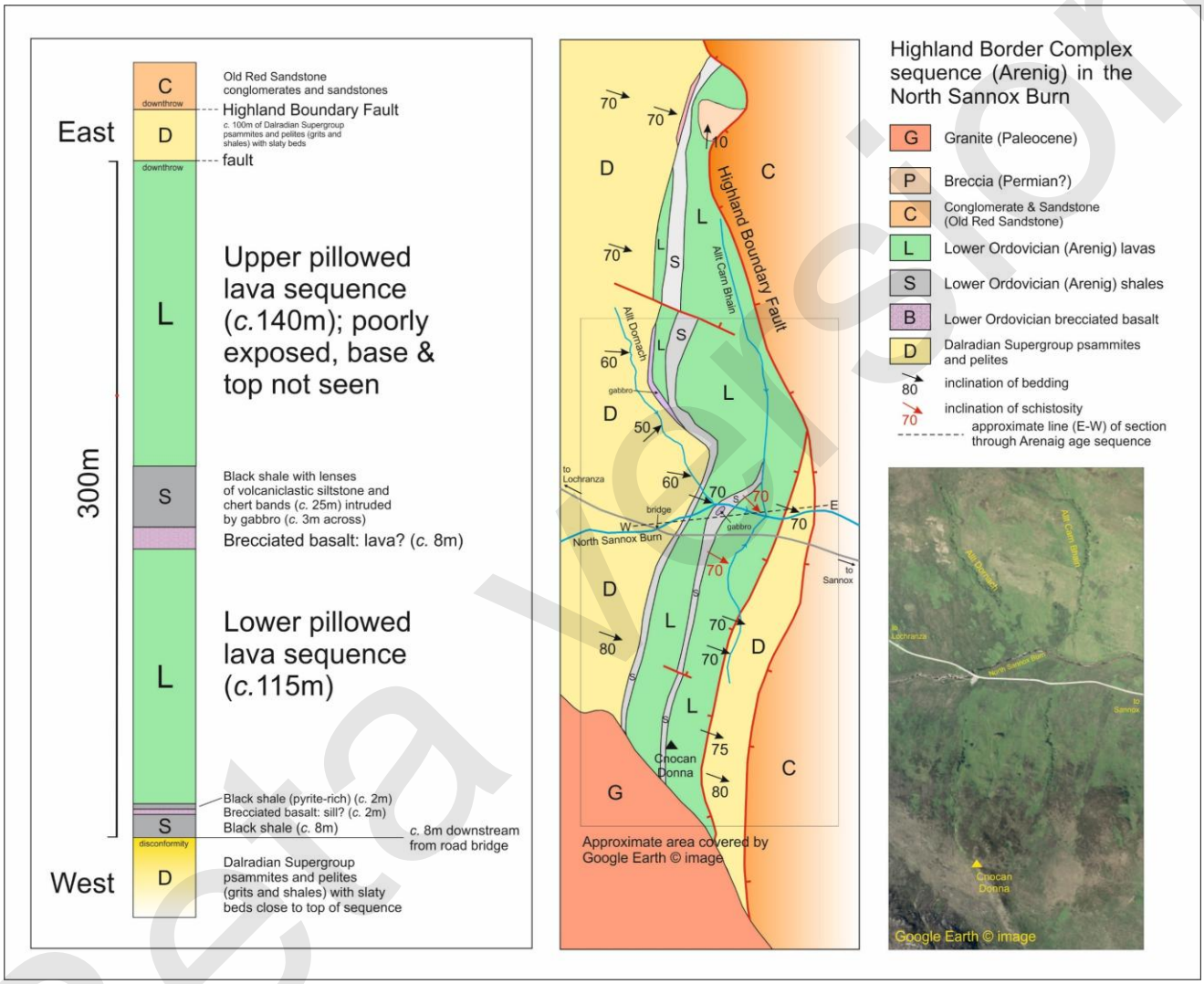


Figure 2-132: Stratigraphic log and geological map of Arenig volcanic and sedimentary units, in NE Arran (after various sources).

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Figure 2-133: Pillowed basaltic lavas of Arenig age in the North Sannox Burn, NE Arran. Pole *ca.* 1 m long. [Photograph courtesy of Ian Williamson]

2.7 The Moine Thrust Zone

2.7.1 Introduction

Compressional tectonics during the Caledonian Orogeny (470-400 Ma) caused major folding and thrusting of the various Hebridean Terrane units (Lewisian Gneiss Complex; the Torridonian Supergroup and Cambro-Ordovician sedimentary rocks, together with rocks of the Moine Supergroup, resulting in a complex zone of deformation (or 'complication') (Figure 2-105; Figure 2-134; Figure 2-135).

On Skye, several nappes, or thrust sheets, are recognised (Peach *et al.* 1907; Peach *et al.* 1910; Bailey 1955). The Lewisian Gneiss Complex and Torridonian Supergroup strata on Raasay are, essentially, undisturbed by the folding and thrusting events.

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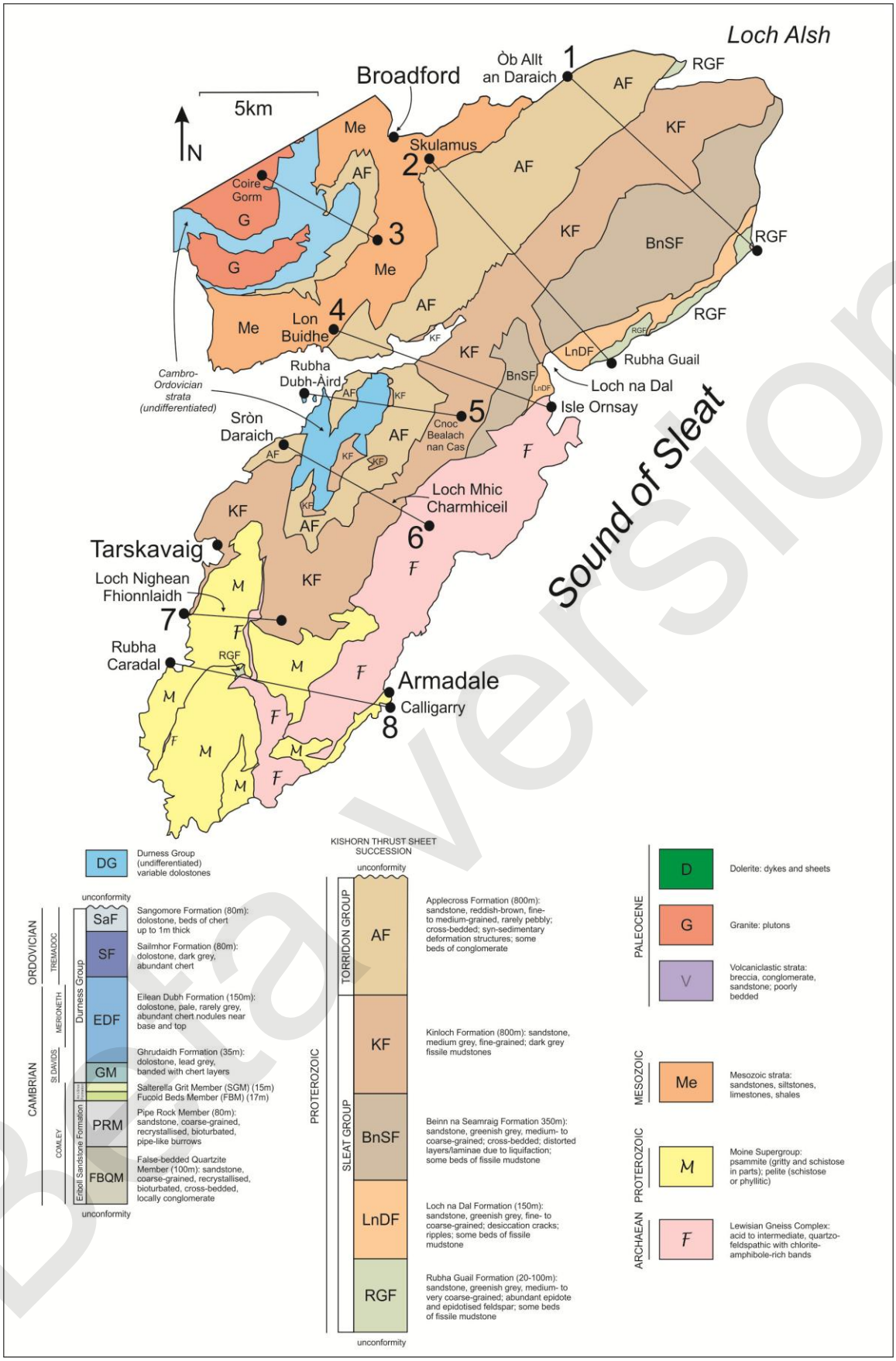


Figure 2-134: Simplified geological map of the main lithological and tectonic components on Sleat and in Strath, with locations of schematic cross-sections in Figure 2.131.

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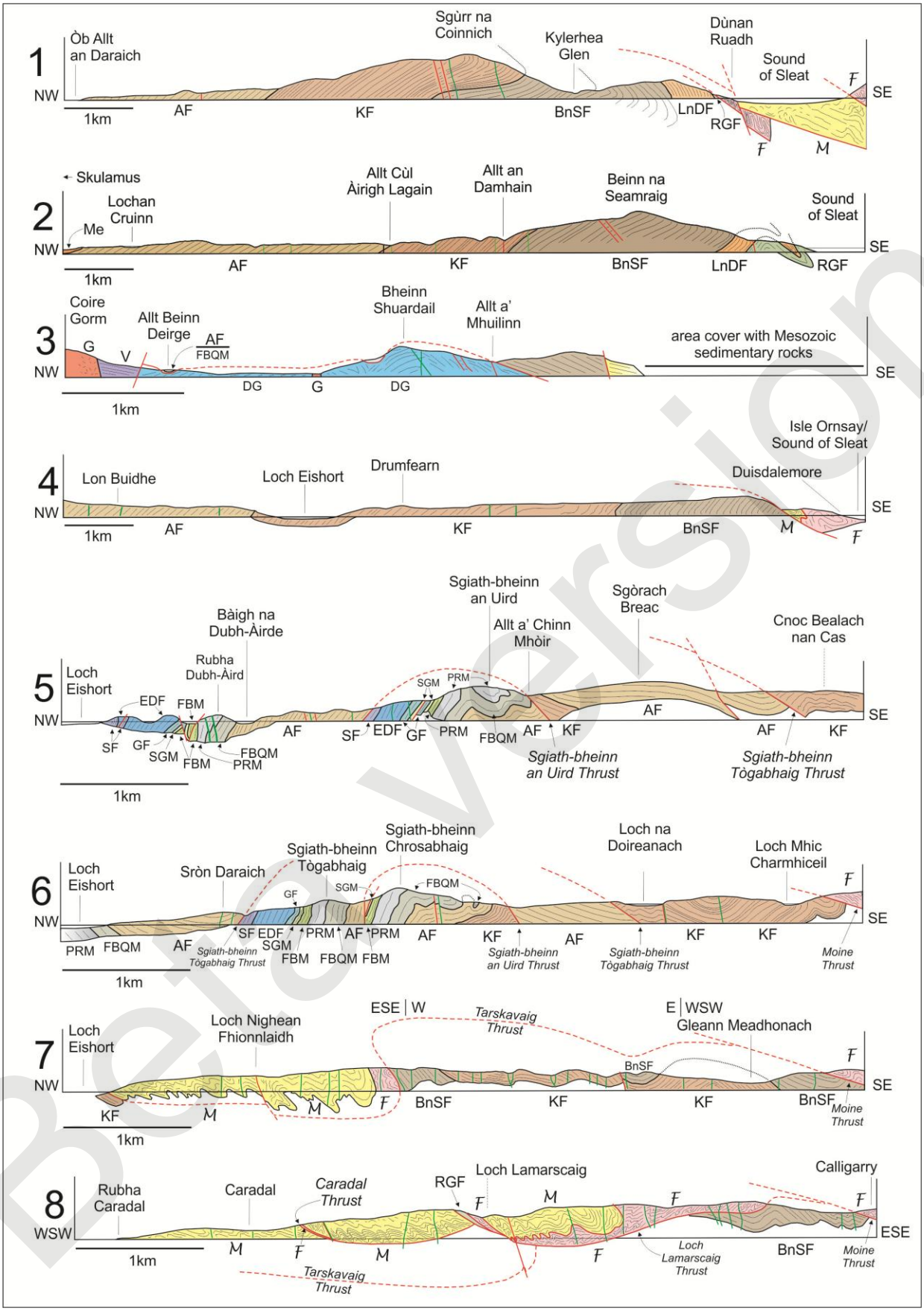


Figure 2-135: Simplified cross-sections illustrating the main lithological units and tectonic components of Sleat and Strath (after Peach *et al.* 1910). See Figure 2.130 for locations of lines of section and key.

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Figure 2-136 illustrates in cross-section the key relationships between the various units within the Moine Thrust Zone on Sleat and in Strath. The complex faulted sequences of orange-brown-weathering Torridonian and white/pale Cambro-Ordovician strata that crop out around Ord on the west side of Sleat is defined/outlined by the Kishorn Thrust Plane (more likely thrust planes) (Bailey 1955) below the Kishorn Thrust Sheet (Nappe). These strata are part of the foreland sequence (Peach *et al.* 1910; Bailey 1955), although it is evident that they have been both folded and faulted (BGS 2002).

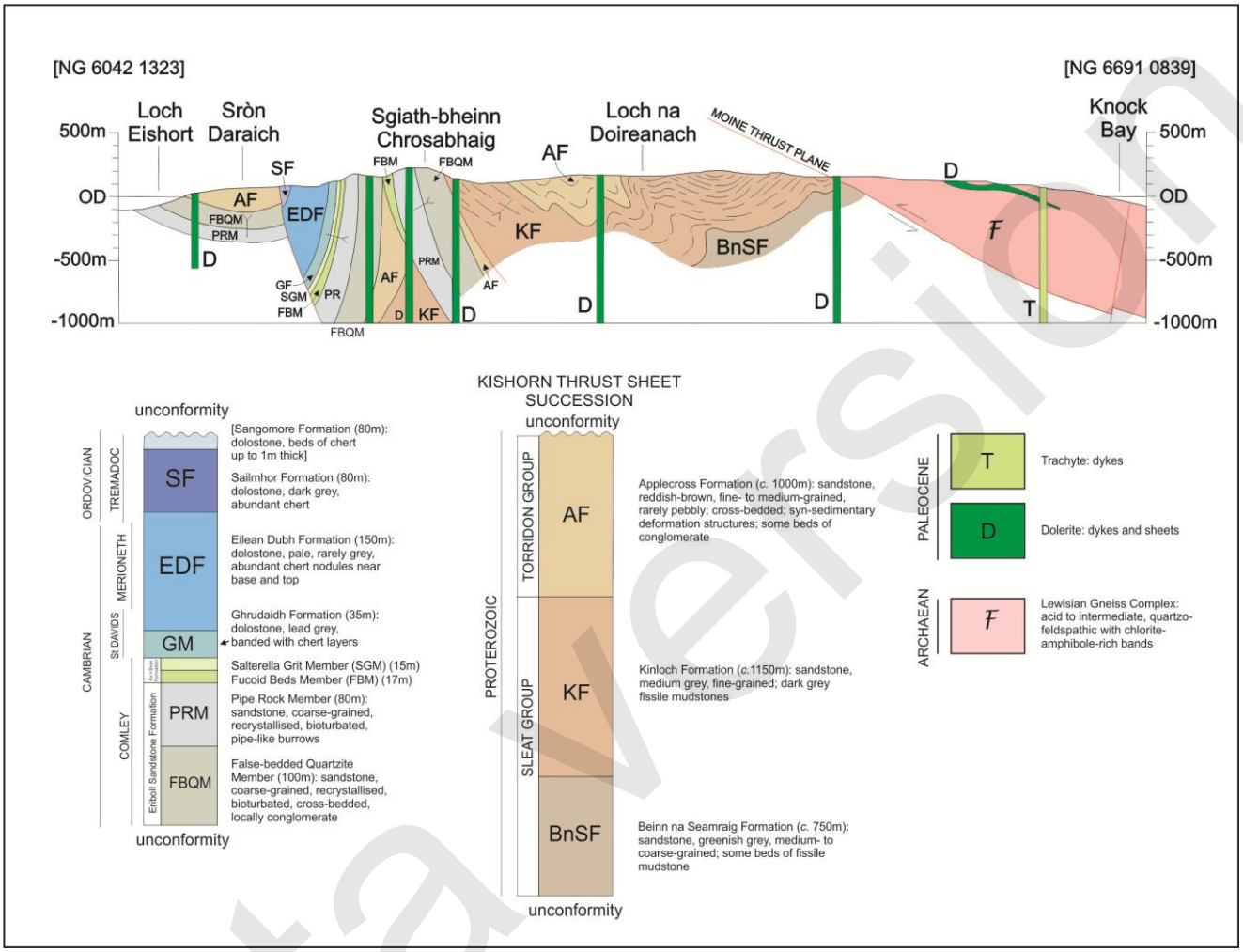


Figure 2-136: Simplified cross-section for the main lithological units and tectonic components between Ord and Knock Bay on Sleat, SE Skye (after BGS 2002).

Further to the NW, in Strath, the Kishorn Thrust Plane occurs on the flanks of Bheinn Suardal, with the Cambro-Ordovician strata considerably modified by folds and faults.

The structurally lowest thrust sheet is the Kishorn Nappe, dominated by the large recumbent Lochalsh Syncline, which is composed of a very thick sequence of (grey, greenish-grey or buff) Torridonian strata of the Sleat and (Lower) Torridon groups, together with gneiss of the Lewisian Gneiss Complex and Cambro-Ordovician strata. The colour difference between the Torridonian strata within the Kishorn Nappe and the orange-brown-weathering units in the foreland sequence can be attributed to incipient metamorphism (Bailey 1955). This colour difference is evident within the folded Torridonian strata within the Kishorn Nappe: the strata on the (lower) right-way-up limb, which dip towards the NW, are reddish-brown, whereas the SE-dipping strata of the (upper) inverted limb are grey or green (Peach *et al.* 1910).

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The overlying Tarskavaig Nappe (Cheeney & Matthews 1965) comprises a complex series of thrust sheets of mylonitised quartz-feldspar -rich meta-sedimentary rocks, of low regional grade (Greenschist Facies), the so-called Tarskavaig Moine Series. Unconformably below these Tarskavaig Moine rocks, within the Tarskavaig Nappe, are mylonitised gneisses of the Lewisian Gneiss Complex. Two thrust planes within the Tarskavaig Moine rocks are recognised, the Caradal and Lamascaig thrusts (Cheeney & Matthews 1965). The Moine Thrust Plane defines the top of the Tarskavaig Nappe, above which is the Moine Nappe, composed of gneiss of the Lewisian Gneiss Complex, together with a minor component of strongly foliated, lineated and folded Moine psammites and pelites (Figure 2-136) (Law & Potts 1987). The gneiss has a relatively strong planar fabric and contains abundant epidote and chlorite, together with porphyroblasts of amphibole. It weathers relatively easily and, therefore, is generally poorly exposed. Both mylonite and (younger) cataclastite fault rocks are recognised at the base of the Moine Nappe (Figure 2-137).



Figure 2-137: Mylonitised gneiss within the Moine Thrust Plane/Zone at the contact between the Moine Thrust Sheet and underlying Torridonian (Supergroup) strata (not seen in this view) of the Kishorn Thrust Sheet in the Allt Duisdale, Sleat, SE Skye. Pole *ca.* 1 m long.

2.8 Caledonian Igneous Rocks

2.8.1 Mull

The post Caledonian Orogeny Ross of Mull Pluton in SW Mull comprises a number of granitic-dioritic bodies with a Rb-Sr age of *ca*. 414 Ma (Halliday *et al.* 1979) and intrudes and thermally metamorphoses Moine Supergroup meta-sedimentary rocks (Figure 2-138; Figure 2-139; Figure 2-140; Figure 2-141; Figure

2-142; Figure 2-143). Cordierite-sillimanite hornfelses have developed from regional metamorphic kyanite-bearing pelitic rocks adjacent to the granite and also occur as xenoliths within the pluton (Figure 2-144). Within the intrusion, the intricate relationships found between quartz-diorite, granite and basic enclaves suggest the co-existence and interaction of basic and silicic magmas.

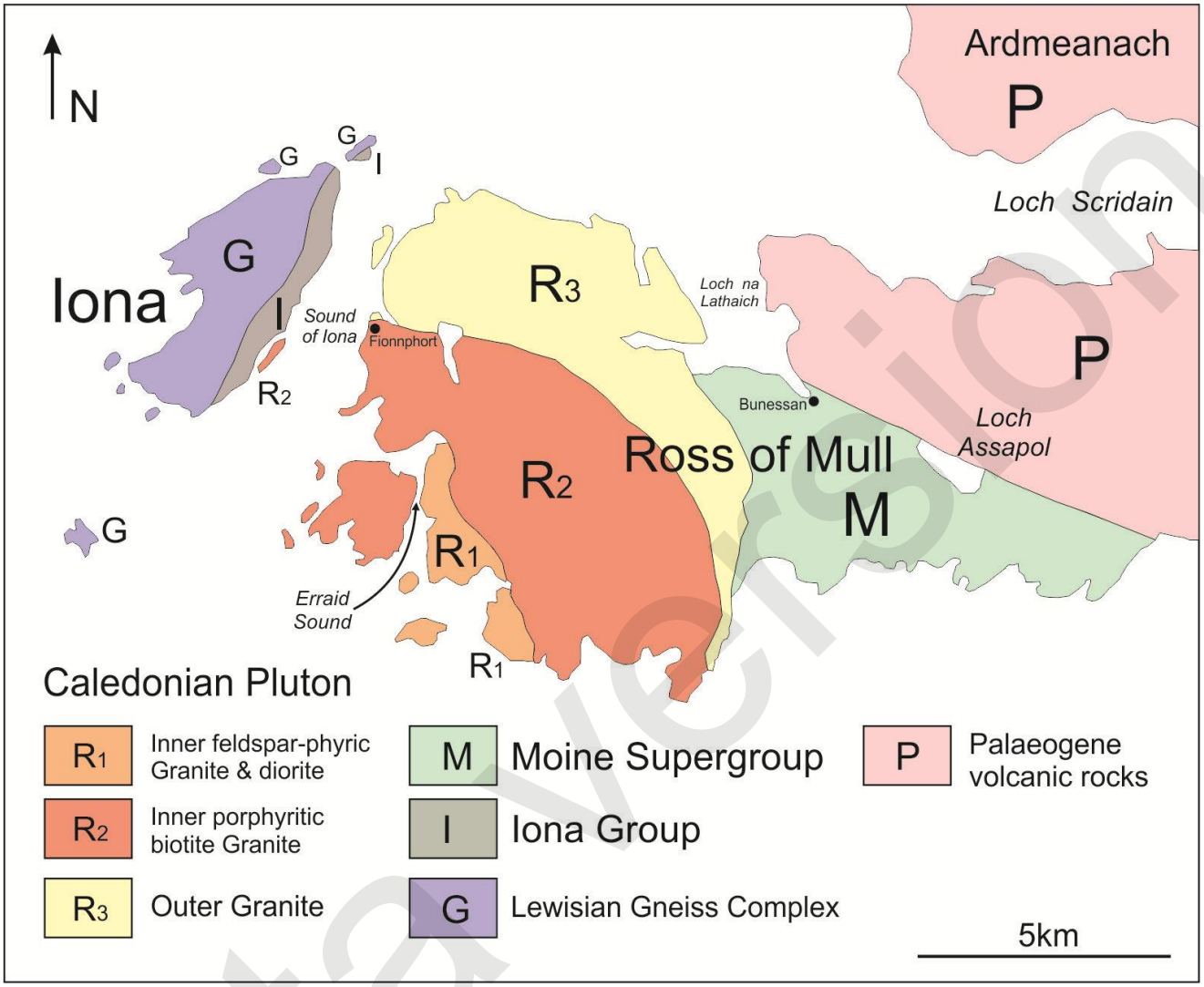


Figure 2-138: Distribution of units of the Ross of Mull Pluton (after Zaniewski *et al.* 2006).

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Figure 2-139: Inner feldspar-phyric Granite, R1, with diorite enclaves, Erraid Sound, SW Mull.



Figure 2-140: Detail of Inner feldspar-phyric Granite, with diorite enclaves, Erraid Sound, SW Mull. Compass *ca*. 10 cm long.

PROVISIONAL



Figure 2-141: Detail of Inner feldspar-phyric Granite, with diorite enclaves, Erraid Sound, SW Mull. Coin *ca*. 24 mm across.



Figure 2-142: Contact zone between the Outer Granite of the Ross of Mull Pluton and country-rock Moine Supergroup psammites and pelites. The pale rock is the granite, and the dark sheets are of diorite. Moine meta-sedimentary rocks form much of the dark layered material close to sea level.



Figure 2-143: Detail of contact zone between the Outer Granite of the Ross of Mull Pluton and country-rock Moine Supergroup psammites and pelites. The pale rock is the granite, and the thick dark sheets are of diorite. Xenoliths of dark, laminated Moine meta-sedimentary rocks approximately maintain their pre-intrusion orientation. Pole *ca.* 1 m long. [Photograph courtesy of Ian Williamson]



Figure 2-144: Regional metamorphic kyanite (blue) schist of the Moine Supergroup partially altered ('overprinted') to cordierite (pink) hornfels close to the margin of the Ross of Mull Pluton, central Ardalanish Bay, SW Mull. Coin *ca.* 24 mm across.

Minor intrusions of Caledonian age include various felsic types and lamprophyres. The felsic dykes are most common in the vicinity of the Ross of Mull Pluton, and near to the Strontian Pluton east of the Paleocene Morvern lava pile on Morvern on the Scottish Mainland (Johnstone & Mykura 1989).

2.9 Old Red Sandstone (ORS)

2.9.1 Introduction

The post Caledonian Orogeny Old Red Sandstone (ORS) sedimentary sequences of Scotland are mainly of Devonian in age, although parts may be Late Silurian or Early Carboniferous. These strata were deposited in response to post orogenic uplift and are dominated by alluvial fan, fluvial and lacustrine sequences (Marshall 2024).

They comprise thick and geographically extensive successions of continental sedimentary and volcanic rocks deposited during and after the erosion of the Caledonian orogenic belt in response to the transition from active orogenesis to post-orogenic collapse and stabilisation within intramontane and marginal basins. The ORS sequences are distributed across much of Scotland, notably in the Midland Valley, Orkney and the Moray Firth region, together with other smaller scattered outcrops. These sequences record the interplay of tectonics, climate, sediment supply and evolving palaeogeography during Devonian time. The ORS basins were structurally controlled, commonly forming as half-grabens and pull-apart basins associated with major fault systems. Basin architecture varies regionally, reflecting differing tectonic controls, subsidence rates and proximity to uplifted source areas.

The ORS is conventionally divided into Lower, Middle and Upper successions, although correlations between basins are often problematic due to strong lateral facies variation and tectonic compartmentalization. The Lower ORS successions are typically coarse-grained and volcanically influenced, reflecting active tectonism and high relief. Middle ORS deposits commonly record more stable basin conditions, while Upper ORS strata show renewed tectonic influence and increasing climatic variability. These subdivisions are broadly temporally rather than lithostratigraphically uniform.

ORS sedimentation was entirely continental, dominated by alluvial, fluvial, lacustrine and aeolian environments. Coarse conglomerates and breccias accumulated proximal to basin margins, forming alluvial fan systems sourced directly from adjacent fault scarps. Fluvial systems range from braided, gravel-rich rivers in tectonically active settings, to more mature, sand-dominated rivers in lower-relief basins. Extensive floodplain deposits, palaeosols and ephemeral lacustrine sediments reflect seasonal hydrological regimes and strong climatic control. Large perennial lakes developed in some basins, particularly in the Orcadian Basin, producing finely laminated lacustrine sediments that preserve exceptional fossil assemblages.

Volcanism is a significant component of the Lower ORS sequences, comprising basaltic and andesitic lavas, volcaniclastic rocks and intrusive bodies in several basins, notably the Midland Valley. These volcanic units provide important stratigraphic markers and local age constraints and demonstrate that the ORS basins were not purely sedimentary but formed within a tectonically and magmatically active continental setting.

ORS sedimentation occurred under generally semi-arid to seasonally arid climates, inferred from red bed coloration, evaporitic features, calcrete development and palaeosols. Climatic variability exerted a strong influence on sedimentary processes, controlling river discharge, lake levels and sediment preservation. Sediment supply was dominated by erosion of the Caledonian highlands, producing clast assemblages

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rich in metamorphic and igneous lithologies. Provenance studies indicate progressive unroofing of the orogen, with younger ORS deposits recording erosion from deeper crustal levels.

The ORS of Scotland has a significant and important fossil record, particularly of early vertebrates and plants. Lacustrine deposits of the Orcadian Basin preserve exceptional fish faunas which provide key insights into Devonian vertebrate evolution. Terrestrial plant fossils record the expansion of vascular plants and the development of early terrestrial ecosystems which had a significant effect on weathering rates, sediment supply and basin geochemistry.

Upwards, the ORS grades into Carboniferous successions in some regions, reflecting renewed subsidence, marine incursions and climatic change. Thus, the ORS forms a critical transitional unit between orogenic collapse and later Palaeozoic basin development (see below).

2.9.2 Arran

Sandstones and conglomerates of the Lower ORS form a thick arcuate outcrop east and south of the Paleocene North Arran Granite Pluton; part of the succession is repeated on the SE side of the Central Arran Ring-complex (Chapter 9) (Figure 2-145; Figure 2-146; Figure 2-147). These strata, which total *ca.* 1200 m in thickness, are faulted against Dalradian Supergroup meta-sedimentary rocks (see above), younger sedimentary rocks, and the North Arran Granite Pluton in east Arran, but on the west side of Glen Rosa they lie unconformably on Dalradian Supergroup strata. Clasts of schistose gritty meta-sandstone occur in conglomerates low in the succession, derived from local Dalradian sources. However, abundant pinkish quartzite boulders and cobbles, for example, in conglomerates near the (abandoned) Glen Sannox baryte mine workings (Chapter 14), have no local source and match most closely Argyll Group (Dalradian) quartzites on Islay and Jura. Sparse plant remains (*Psilophyton princeps, var. ornatus*) have been found high in the succession in Glen Shurig (Tyrrell 1928).

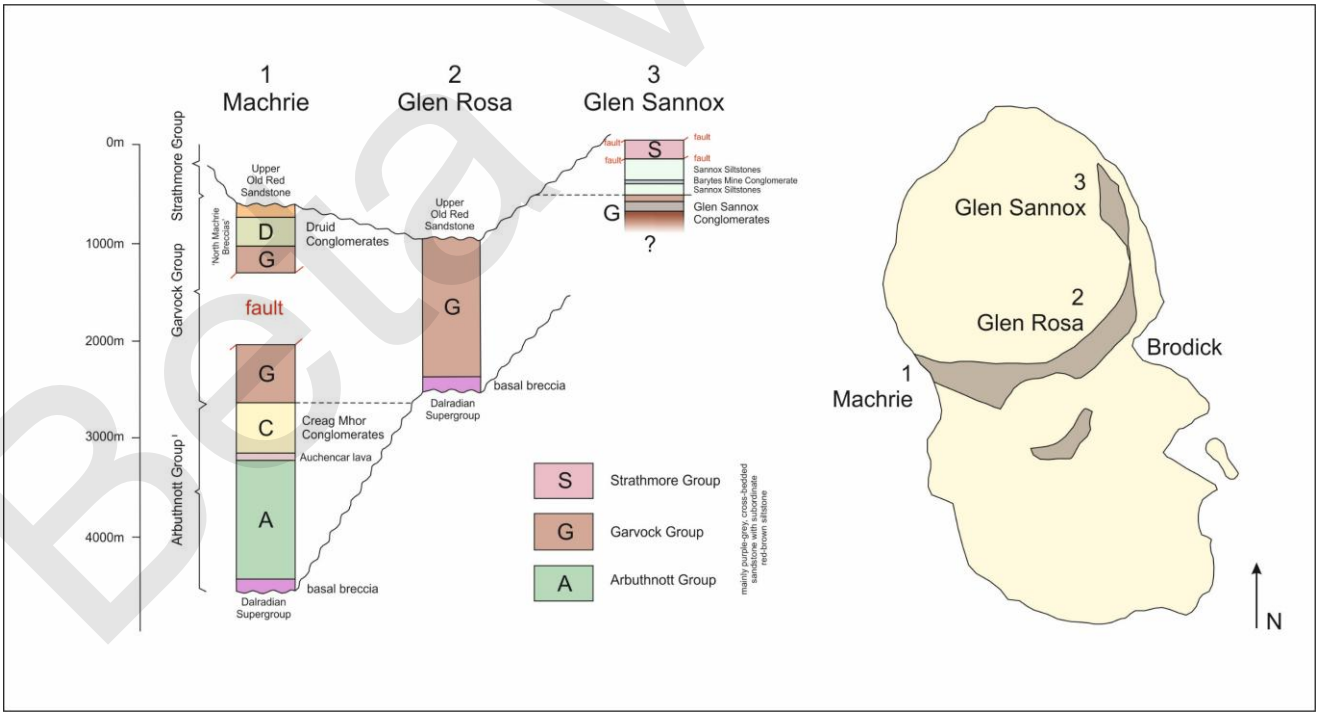


Figure 2-145: Stratigraphic logs for Lower ORS sequences, Isle of Arran (after various sources).

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Figure 2-146: Steeply inclined Lower ORS strata forming the inland crag, north of Machrie, west Arran.



Figure 2-147: Lower ORS conglomerates and sandstones, north of Machrie, west Arran.

Upper ORS strata occur above all of the Lower ORS sequences, but, in contrast to the Scottish Mainland occurrences, there is no obvious intervening unconformity. In the east, the sequence is *ca*. 90 m thick and comprises sandstone with conglomerate beds containing clasts not only of local origin (vein quartz and

Dalradian lithologies) but also of possible Islay and Jura quartzite (Figure 2-148; Figure 2-149). Similar rocks crop out SE of the Paleocene Central Arran Ring-complex. On the west coast, conglomerates and sandstones of the North Machrie Breccias total *ca.* 375 m in thickness, with the proportion of sandstone increasing eastwards.



Figure 2-148: Upper ORS breccia, Clach an Fhionn, Corrie, NE Arran. Pole *ca.* 1 m long.



Figure 2-149: Upper ORS sandstones, Clach an Fhionn, Corrie, Isle of Arran. Pole *ca.* 1 m long.

Brevet

The Arran ORS sequences represent alluvial fan deposits similar to those present on the northern edge of the Midland Valley on the Scottish Mainland. They were deposited by braided river systems, with the sediment load derived from the north. Strongly desiccating conditions are indicated by the presence of caliche deposits (cornstones), which are especially well developed at the base of the succession at 'Hutton's Unconformity' NE of Loch Ranza, where the carbonate pedogenesis extends for *ca*. 50 cm into Dalradian rocks below the unconformity. There, the caliche-bearing Upper ORS beds above the unconformity are, however, assigned to the Kinnesswood Formation at the base of the Carboniferous succession (see below).

Volcanic rocks within the ORS succession of Arran are limited to an (?)olivine andesite lava within the Lower ORS south of the North Arran Granite Pluton and (altered) olivine basalt and andesite lavas interbedded with the Upper ORS strata north of North Glen Sannox. The olivine andesite lava has been compared with lavas in the Lower ORS of the Midland Valley, whereas the olivine basalt lavas are similar to lavas low in the Carboniferous succession of the Midland Valley.

2.9.3 Mull

Basaltic and andesitic lavas belonging to the Lower ORS Lorn Plateau Volcanic Formation crop out in the core of the Loch Don Anticline in SE Mull. Conglomerates and marly sandstones, possibly of similar age, occur on Frank Lockwood's Island, SE of Loch Buie, off south Mull.

2.10 Carboniferous

2.10.1 Introduction

Carboniferous rocks typically unconformably overlie Devonian Old Red Sandstone (ORS) strata, marking a major shift in tectonic regime and depositional style.

The Carboniferous successions of Scotland document a critical phase of post-Caledonian crustal evolution, recording the interaction of intracontinental tectonics, sedimentary processes, climate change and magmatism during the Late Palaeozoic. Preserved mainly within fault-bounded basins of the Midland Valley and adjacent regions, these strata reflect deposition within a tectonic regime dominated by oblique-slip deformation, influenced by far-field stresses associated with the Variscan Orogeny.

The Carboniferous basins developed through the reactivation of long-lived Caledonian and older basement structures. Strike-slip and transtensional (i.e. strike-slip and extension) faulting produced a mosaic of linked depocentres characterised by strong lateral thickness variations and abrupt facies changes. The Midland Valley is therefore best interpreted as a composite tectono-sedimentary domain, with individual basins evolving asynchronously in response to variable subsidence and sediment supply.

Carboniferous successions span the Tournaisian to Moscovian stages and are conventionally subdivided into Lower (Dinantian) and Upper (Silesian) intervals. However, correlation between basins is hindered by facies heterogeneity, non-deposition and erosion, emphasising the importance of basin-scale stratigraphic frameworks. Broadly, Lower Carboniferous successions reflect more active tectonism and marine influence, whereas Upper Carboniferous deposits record increasingly continental conditions.

Lower Carboniferous sedimentation occurred under conditions of active faulting and fluctuating relative sea level, producing complex alternations of marine and non-marine facies. Shallow-marine limestones

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developed episodically during intervals of reduced clastic influx, while siliciclastic systems record deltaic, fluvial and lacustrine environments fed by erosion of the Caledonian hinterland. Rapid/abrupt lateral facies transitions highlight the sensitivity of these systems to subtle changes in accommodation space.

Upper Carboniferous successions are dominated by coal-bearing cyclothems, comprising repeated vertical successions of mudstone, sandstone, palaeosol and coal. These cycles are widely interpreted as responses to high-frequency glacio-eustatic sea level fluctuations driven by Gondwanan ice sheets. Coal accumulated in extensive equatorial mires on coastal plains and delta tops under humid tropical climates, with seam distribution strongly controlled by subsidence rate and fault activity.

A distinctive feature of the Scottish Carboniferous is widespread intraplate basaltic magmatism, particularly in the Midland Valley. Lavas, sills and volcanic centres reflect mantle melting associated with lithospheric thinning in a transtensional setting. Volcanism exerted strong local controls on sedimentation and provides important stratigraphic markers within predominantly continental successions.

Carboniferous strata within the Hebridean Igneous Province are restricted to NE Arran between Corrie and Glen Cloy, and on the Morvern coast on the Sound of Mull.

2.10.2 Arran

Intensively faulted Carboniferous strata crop out on the NE coast, and between Corrie and Glen Cloy (Figure 2-150; Figure 2-151; Figure 2-152; Figure 2-153; Figure 2-154; Figure 2-155; Figure 2-156; Figure 2-157; Figure 2-158). They range from sandstone and mudstone of the Inverclyde Group (Tournaisian) to siltstone, seat-earth and sandstone of the Coal Measures (Westphalian). The sequence includes the fossiliferous Corrie Limestone, which contains abundant brachiopod *Productus latissimus* and is equivalent to the Hurlet Limestone at the base of the Lower Limestone Formation (latest Visean) on the Scottish Mainland. Olivine basalt lavas and volcaniclastic rocks are present in the lower part of the succession, exposed on the Corrie foreshore and on the NE coast. These lavas overlie sandstones of the Clyde Sandstone Formation (Tournaisian) and are equated with lavas belonging to the Clyde Plateau Volcanic Formation of the Strathclyde Group. Altered basalt lavas in the Merkland Burn near Brodick Castle overlie sandstones and mudstones of the Limestone Coal Formation (Namurian).

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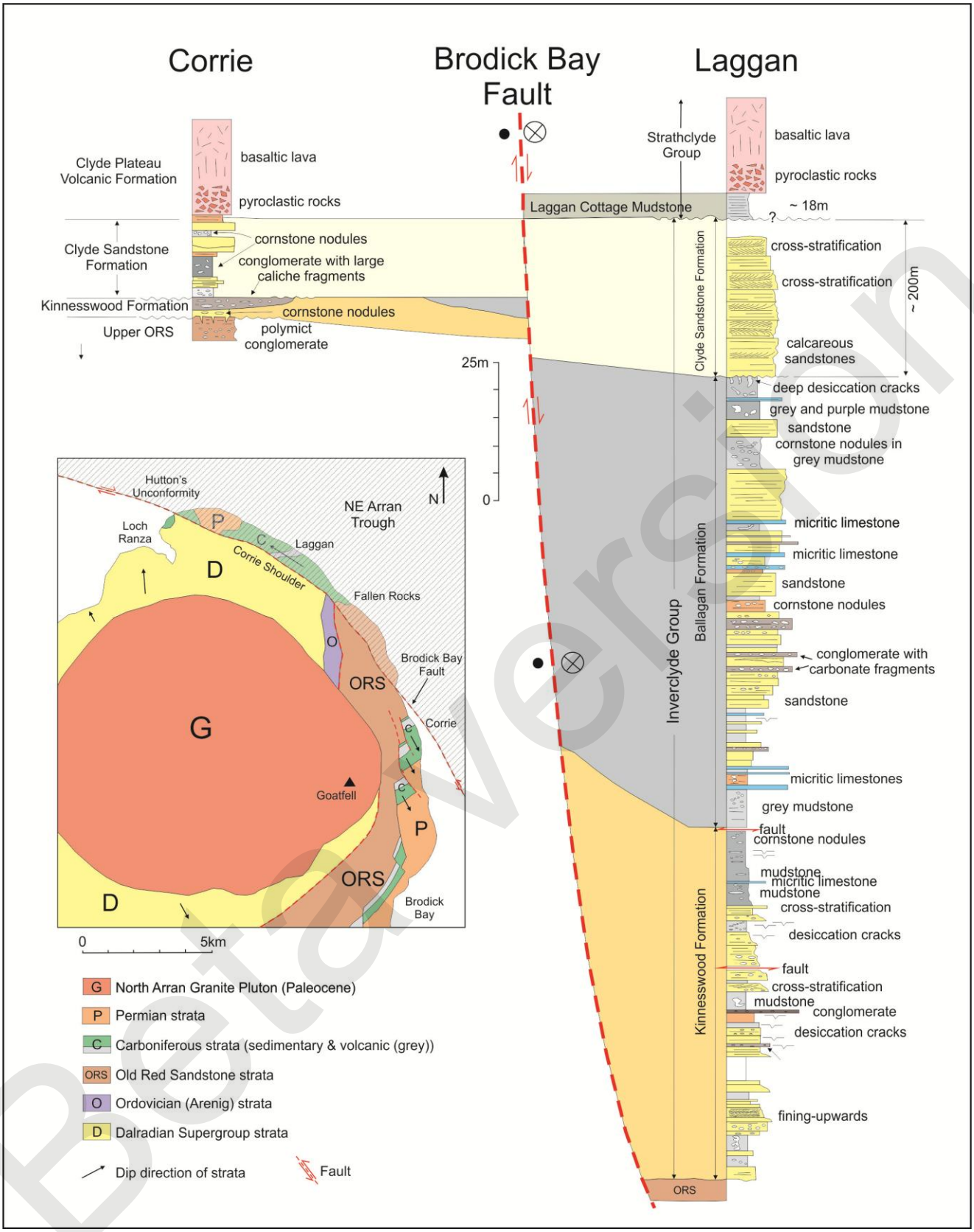


Figure 2-150: Stratigraphic logs for Carboniferous sequences, NE Arran (after Young & Caldwell 2012).

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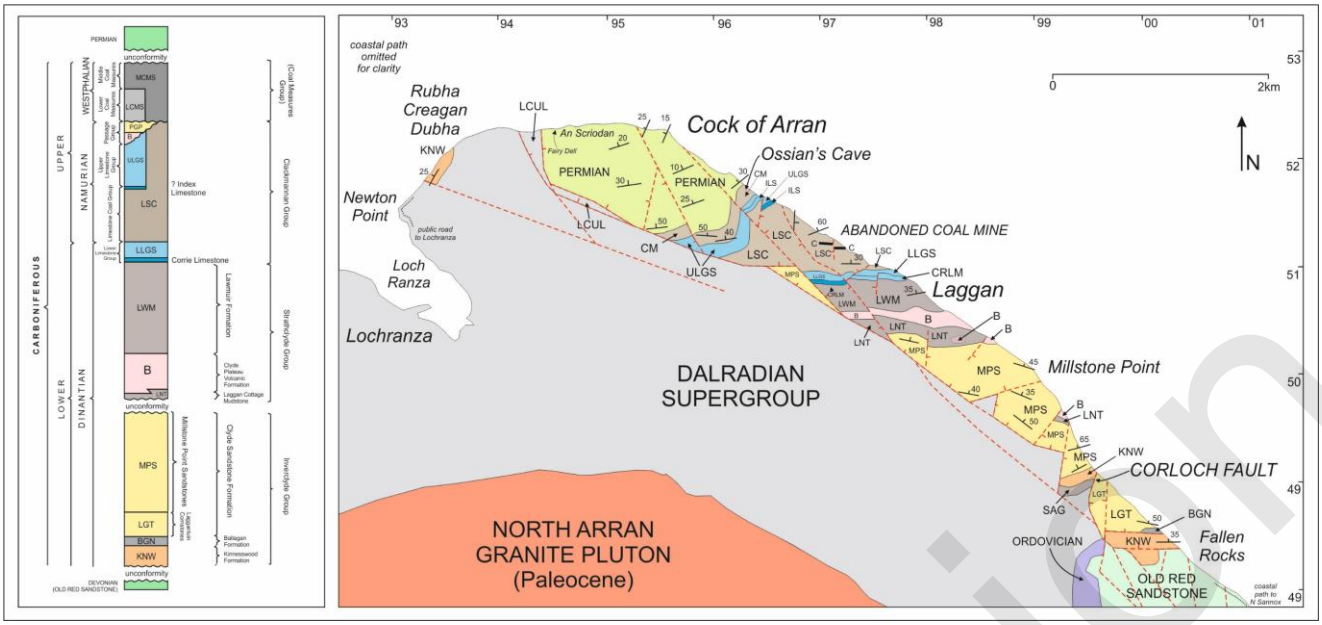


Figure 2-151: Carboniferous stratigraphic log and geological map, NE Arran (after various sources).



Figure 2-152: Hutton's Unconformity, North Newton, north Arran. The pole sits on caliche-bearing strata, assigned to the Kinnesswood Formation of Carboniferous age. Steeply inclined Dalradian Supergroup psammites, below the unconformity, are exposed bottom-right. Pole *ca.* 1 m long.

Preview version



Figure 2-153: Cross stratified Kinnesswood Formation sandstones, Clach an Fhionn, Corrie, NE Arran. Pole *ca*. 1 m long.



Figure 2-154: Detail of Kinnesswood Formation sandstones, Clach an Fhionn, Corrie, NE Arran. Coin *ca*. 24 mm across.



Figure 2-155: Carboniferous lava at Clach an Fhionn, Corrie, NE Arran. Pole *ca.* 1 m long.



Figure 2-156: Carboniferous volcaniclastic unit at Clach an Fhionn, Corrie, NE Arran. Pole *ca.* 1 m long.



Figure 2-157: Amygdaloidal Carboniferous lava between Laggan and Millstone Point, NE Arran. Pole *ca*. 1 m long.



Figure 2-158: Upper Carboniferous Corrie Limestone, Ferry Rock, Corrie, NE Arran. Pole *ca*. 1 m long.

Proof version

2.10.3 Morvern

A small, faulted inlier consisting of over 100 m of sandstones and mudstones with thin fireclays and (uneconomic) coal seams underlies Permo-Triassic beds at Inninmore on Morvern on the Scottish Mainland. Fossil plants, including *Asterophyllites charaeformis*, *A. equisetiformis*, *Calamites cisti*, *C. schutzeiformis*, *Mariopteris muricata*, *Neuropteris gigantea* and *Samaropsis* sp., indicate an early Coal Measures (Westphalian) age for these deposits (Lee & Bailey 1925; Johnstone & Mykura 1989). Despite its limited extent, the occurrence is of some importance since it is one of very few outcrops of Carboniferous rocks in western Scotland.

2.11 Permian

2.11.1 Introduction

The Permian rocks of Scotland record a fundamental transition in tectonic regime, climate and sedimentary style following the cessation of Carboniferous basin development and the waning influence of the Variscan Orogeny (e.g. Hartley & Watson 2024). During the Permian, Scotland lay within the interior of the supercontinent Pangaea, at progressively increasing northern palaeo-latitudes (10-30°), and experienced predominantly arid to semi-arid climatic conditions. Sedimentation was confined to a limited number of fault-controlled continental basins, reflecting continued reactivation of older structures under a regime of regional lithospheric stability.

Permian strata commonly overlie Carboniferous rocks with marked unconformity, reflecting tectonic reorganisation, erosion and climate change. The transition from coal-bearing Carboniferous successions to red-bed Permian deposits marks a fundamental shift in depositional regime.

Permian successions are preserved mainly within the Midland Valley, notably in the Mauchline Basin, on Arran, and in a small number of isolated onshore and offshore depocentres. Their restricted distribution reflects both limited accommodation space and extensive post-Permian erosion. Permian successions in Scotland form the lower part of the New Red Sandstone Supergroup and are typically thin, discontinuous and laterally variable. They are dominated by red sandstones, conglomerates and mudstones, commonly overlying unconformably folded and faulted Carboniferous strata. Fossil content is sparse, and stratigraphic correlation relies heavily on lithofacies analysis and regional tectonic relationships rather than biostratigraphy.

In many basins, Permian sedimentary rocks are closely associated with basaltic volcanic rocks, which form an important component of the succession and locally define its base. Permian sedimentation was strongly influenced by fault reactivation, particularly along inherited Caledonian and Carboniferous structures. Basins developed as small half-grabens and fault-bounded depressions, with sediment thickness and facies distribution controlled by proximity to active faults.

Unlike the Carboniferous, Permian basins show limited evidence for widespread subsidence or basin linkage. Instead, they represent isolated depocentres within an otherwise tectonically quiescent continental interior. This setting reflects a shift from oblique-slip and transtensional deformation to a more subdued intraplate tectonic regime.

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Permian sedimentation occurred entirely in continental environments, dominated by alluvial fan, ephemeral fluvial and aeolian systems. Coarse conglomerates and breccias accumulated adjacent to basin-bounding faults, forming proximal alluvial fan deposits derived from nearby uplands. These pass basinward into sandstones deposited by ephemeral braided rivers and sheet floods. Aeolian processes were locally significant, reflecting arid climatic conditions and limited vegetation cover. Well-sorted sandstones with large-scale cross-bedding record dune-field development in parts of some basins, although preserved aeolian successions are generally thin and discontinuous. Mudstones and siltstones reflect deposition in ephemeral floodplains, shallow playa lakes and low-energy distal settings. Evaporitic minerals are rare but the pervasive red coloration of the sediments reflects oxidation under arid conditions.

A defining feature of the Permian of Scotland is the dominance of arid to semi-arid climates, contrasting sharply with the humid tropical conditions of the late Carboniferous. The scarcity of coal, palaeosols indicative of vegetation cover, and fossil assemblages reflects this climatic shift.

Sedimentary structures indicate highly seasonal rainfall, with sediment transport dominated by short-lived, high-energy flood events separated by prolonged dry intervals. Weathering was largely physical rather than chemical, contributing to the abundance of coarse detritus in proximal basin settings.

Basaltic volcanism is a key component of the Scottish Permian, particularly in the Midland Valley. Lavas, volcanic vents and associated intrusions are interpreted as products of intraplate magmatism, linked to lithospheric thinning and mantle upwelling following Variscan tectonism. These volcanic rocks are typically alkaline in composition and mark a continuation, albeit at reduced intensity, of the magmatic activity that characterised the Carboniferous. These volcanic units provide valuable stratigraphic constraints within otherwise poorly dated sedimentary successions.

Upwards, the Permian sequences grade into or are overlain by Triassic successions that continue the theme of continental red-bed sedimentation, although with evolving basin configurations and climatic nuances. In many areas, the Permian–Triassic boundary is difficult to define precisely due to poor exposure and limited biostratigraphic control.

Permo-Triassic rocks crop out widely in the Hebrides (Chapter 3), where they are also important constituents of the offshore basins, but it is only on Arran that the Permian and Triassic are separated in published accounts (e.g. Lovell 1991).

2.11.2 Arran

The *ca.* 500 m thick sequence of sandstones and sedimentary breccias comprising the Corrie Sandstone and the Brodick Breccia are of Permian age (Figure 2-159; Figure 2-160; Figure 2-161; Figure 2-162; Figure 2-163). The sandstones are of aeolian origin, with obvious dune bedding and wind polished sand grains (Frederiksen *et al.* 1998). Fossil lightning strikes (fulgurites) have been recognised in the beds at Corrie (Figure 2-164) (Harland & Hacker 1966).

The Brodick Breccia consists of coarse sedimentary breccias and conglomerates with fragments of Dalradian vein quartz and quartzose schist, and agate and basalt clasts derived from Devonian and Carboniferous lavas. They are interpreted as flash-flood deposits, formed when debris was periodically flushed out from wadis. The associated fine-grained rocks are similar to the Corrie Sandstone. The overlying, diachronous and possibly interdigitating Machrie, Glen Dubh and Lamlash Sandstone

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formations are tentatively equated with the Upper Permian to Middle Triassic Sherwood Sandstone Group (Lovell 1991). Olivine basalt lavas in the upper reaches of the Sliddery Water are of Early Permian age.

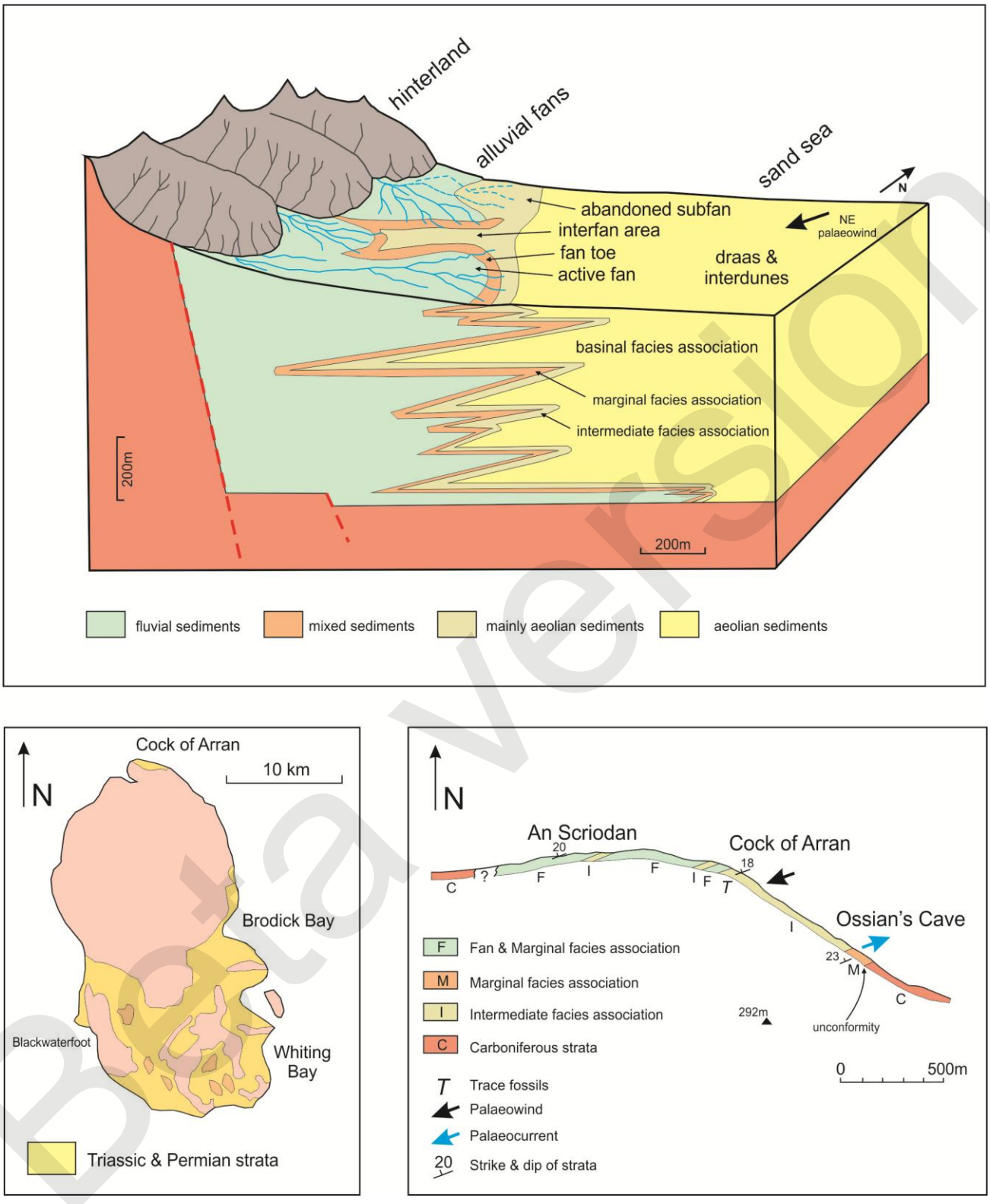


Figure 2-159: Sedimentological model and geological distribution maps for Permo-Triassic strata, Isle of Arran (after various sources).

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Figure 2-160: Permian Breccia and sandstone, Cock of Arran, north Arran. Pole *ca*. 1 m long.



Figure 2-161: Detail of Permian Breccia and sandstone, Cock of Arran, north Arran. Pole ca. 1 m long.



Figure 2-162: Dr McCredy's Bath, excavated out of Permian sandstones, south of Sandstone Harbour, Corrie, NE Arran. Christine Bell for scale.



Figure 2-163: Dune-bedded Permian sandstones, south of Sandstone Harbour, Corrie, NE Arran. Pole *ca.*1 m long.



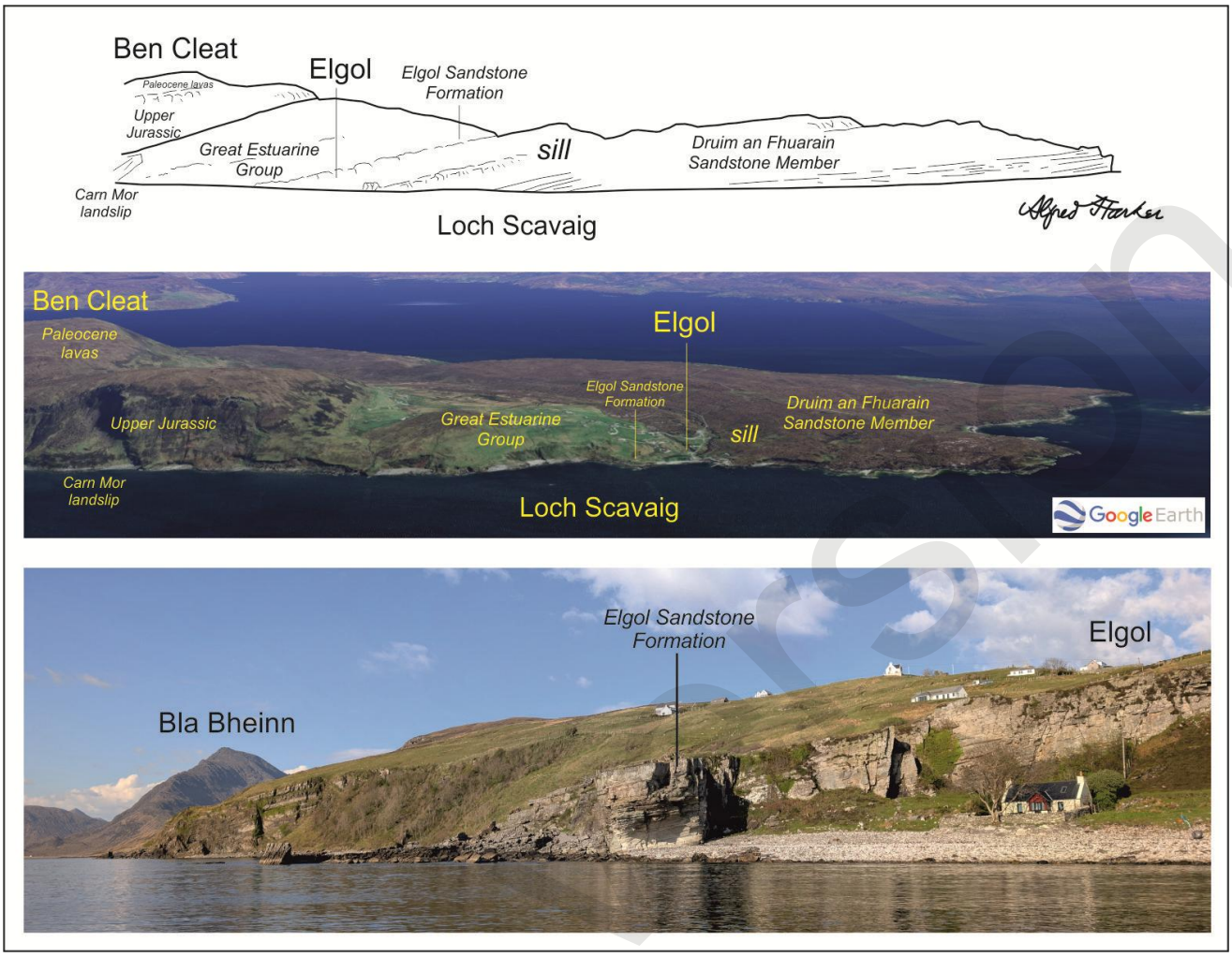
Figure 2-164: Corrie fulgurite (fossil lightning strike), south of Sandstone Pier, Corrie, NE Arran.

2.12 Intrusions of Carboniferous and Permian age

Minor intrusions of Carboniferous and Permian age are widespread through the southern Highlands and extend into the western Highlands and Islands. There are two main suites: Stephanian tholeiitic rocks and Visean to Early Permian alkali basalts and lamprophyres. On Arran, the former includes a thick quartz-dolerite dyke at Imachar. East of the Palaeogene lavas on Morvern, isolated quartz-dolerite plugs and west- to WNW-trending quartz dolerite dykes, which crop out between the Paleocene lavas and the Silurian-Devonian Strontian Pluton, are regarded as part of the Stephanian tholeiitic suite. At Gribun in western Mull, Moine rocks are intruded by a dyke of olivine nephelinite exposed at low water, which contains a suite of xenoliths and megacrysts of lower crustal and possibly upper mantle origin (Upton *et al*. 1998). This dyke is similar to numerous other xenolith-bearing intrusions of Carboniferous and Permian age in the western Highlands and Islands and the Midland Valley. The xenoliths and xenocrysts in these intrusions provide valuable information about the nature of the Lower Crust and Upper Mantle at the start of the Mesozoic Period (Chapter 3) (e.g. Upton *et al*. 1998).

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3 Mesozoic Rocks



Jurassic sedimentary sequence, Strathaird, Skye

3.1 Introduction

Sequences of Triassic strata in the Inner Hebrides and on Arran are thin, discontinuous and only locally preserved, reflecting limited depositional accommodation space and subsequent erosion. Deposition was controlled by the formation of half-grabens during post-Variscan (Orogeny) intraplate deformation under arid to semi-arid climatic conditions at a palaeo-latitude of 15-25° N. Lithologies are dominated by non- to sparsely-fossiliferous red-bed sandstones, conglomerates and mudstones, with pervasive oxidation indicating prolonged subaerial exposure. Sedimentary structures include planar and trough cross-stratification, channel scours and mud cracks, consistent with ephemeral fluvial systems, alluvial fans and playa-lake environments. Grain size commonly decreases basinward, reflecting short transport distances from adjacent Caledonian basement highs. Sedimentation was controlled primarily by tectonic subsidence rather than eustatic processes.

Triassic sedimentation exploited pre-existing Caledonian and Variscan structural lineaments, which defined basin geometry and sediment dispersal patterns. Normal faulting created localized accommodation space, although subsidence rates were low and episodic. These structures established the tectonic framework, later reactivated during Jurassic rifting, exerting long-term control on basin

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architecture. Although volumetrically minor, the Triassic deposits are significant as indicators of early crustal extension and stress reorganisation preceding full rift development.

The Triassic–Jurassic boundary marks a major change in the depositional regime in the Inner Hebrides. Continental red-bed sedimentation was replaced by marine conditions, reflecting increased rates of lithospheric extension and subsidence associated with the initial stages of Pangaea break-up. Marine transgression was structurally controlled and diachronous, with Jurassic strata locally overstepping Triassic deposits and directly overlying older 'basement'.

This transition records a shift from internally drained continental basins to marine-connected rift basins, with accommodation space increasingly driven by tectonic subsidence rather than climate alone.

Jurassic sedimentation in the Inner Hebrides occurred within the Hebridean Basin, an elongate rift system composed of asymmetric half-grabens bounded by major normal faults. Basin geometry was highly variable, producing significant lateral thickness and facies variations over short distances. Fault reactivation was common throughout the Jurassic, resulting in syn-sedimentary deformation, growth strata (sediments deposited during tectonic deformation), and local unconformities.

The Inner Hebrides formed the onshore expression of a western rift branch, distinct from the North Sea rift system to the east. Basin subsidence resulted from a combination of mechanical stretching and thermal relaxation, progressively increasing accommodation space through time.

Early Jurassic strata record the establishment of shallow-marine shelf environments across the Inner Hebrides. Mudstones dominate, with subordinate fine-grained sandstones deposited under storm-influenced conditions. Sedimentary structures include hummocky cross-stratification, bioturbation and thin event beds, reflecting episodic high-energy conditions on a generally low-energy shelf.

Marine faunas, particularly ammonites and bivalves, indicate open marine circulation and provide high-resolution biostratigraphic control. Early Jurassic successions record relatively uniform shelf sedimentation compared to later Jurassic strata, although thickness variations attest to ongoing fault-controlled subsidence. Episodes of reduced bottom-water oxygenation are locally recorded by dark organic mudstones and ironstones, linking Inner Hebridean basins to broader Early Jurassic oceanographic perturbations.

Middle Jurassic successions display maximum facies diversity and stratigraphic complexity. The Inner Hebrides preserve classic examples of shallow-marine to marginal-marine deposition within restricted rift basins. Sedimentary environments included lagoonal, tidal flat, deltaic and shallow shelf systems, with strong lateral variability controlled by basin morphology and fault activity.

Lithologies include interbedded mudstones, siltstones and sandstones, together with limestones, indicating fluctuating salinity, water depth and sediment supply. Carbonate beds reflect periods of reduced siliciclastic input and restricted circulation. Cyclic sedimentation is a prominent feature, reflecting interaction between relative sea-level change, subsidence and sediment influx. Many cycles record shallowing-upward trends from offshore mudstones to marginal marine or deltaic sandstones, terminated by marine flooding surfaces. Restricted water circulation within these fault-bounded basins produced pronounced geochemical variability and localized fossil assemblages, emphasising the highly partitioned nature of Middle Jurassic Inner Hebridean basins.

Upper Jurassic strata record a transition towards more uniform marine conditions. Mudstones dominate, with reduced proportions of sandstones and carbonates, reflecting deepening shelf environments and diminished clastic supply. Continued subsidence increased basin connectivity, reducing the degree of environmental restriction characteristic of the Middle Jurassic.

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Throughout the Jurassic, sedimentation in the Inner Hebrides was closely coupled to active normal faulting. Growth strata, abrupt thickness changes and facies juxtaposition across faults demonstrate ongoing syn-sedimentary deformation. Fault-controlled subsidence dictated shoreline position, water depth and sediment pathways, producing highly variable stratigraphic architectures. Structural inheritance played a critical role, with Triassic and older faults repeatedly reactivated. The resulting basin configurations influenced depositional systems at all scales, from regional facies belts to local sedimentary cycles.

Climatically, the Triassic–Jurassic interval records a transition from arid continental climates to warm, greenhouse marine conditions. Rising global sea levels through the Jurassic enhanced marine flooding of the Inner Hebridean basins, while climatic stability promoted widespread carbonate and mudstone deposition during periods of reduced clastic input.

Cretaceous rocks of the Inner Hebrides are sparse, discontinuous and largely preserved as remnants within fault-controlled basins and erosional outliers, reflecting widespread uplift and erosion during early (Paleocene) North Atlantic rifting. Deposition was dominated by marine mudstones and chalk, indicating renewed marine transgression and low clastic sediment supply. These sediments record regional thermal subsidence following Jurassic rifting and progressive marine inundation of the Hebridean margin. Much of the original Cretaceous cover was subsequently removed during Paleocene uplift associated with the onset of the North Atlantic Igneous Superprovince (NAIS), leaving only fragmentary onshore records that nonetheless confirm a phase of open-marine shelf sedimentation prior to volcanic overprinting.

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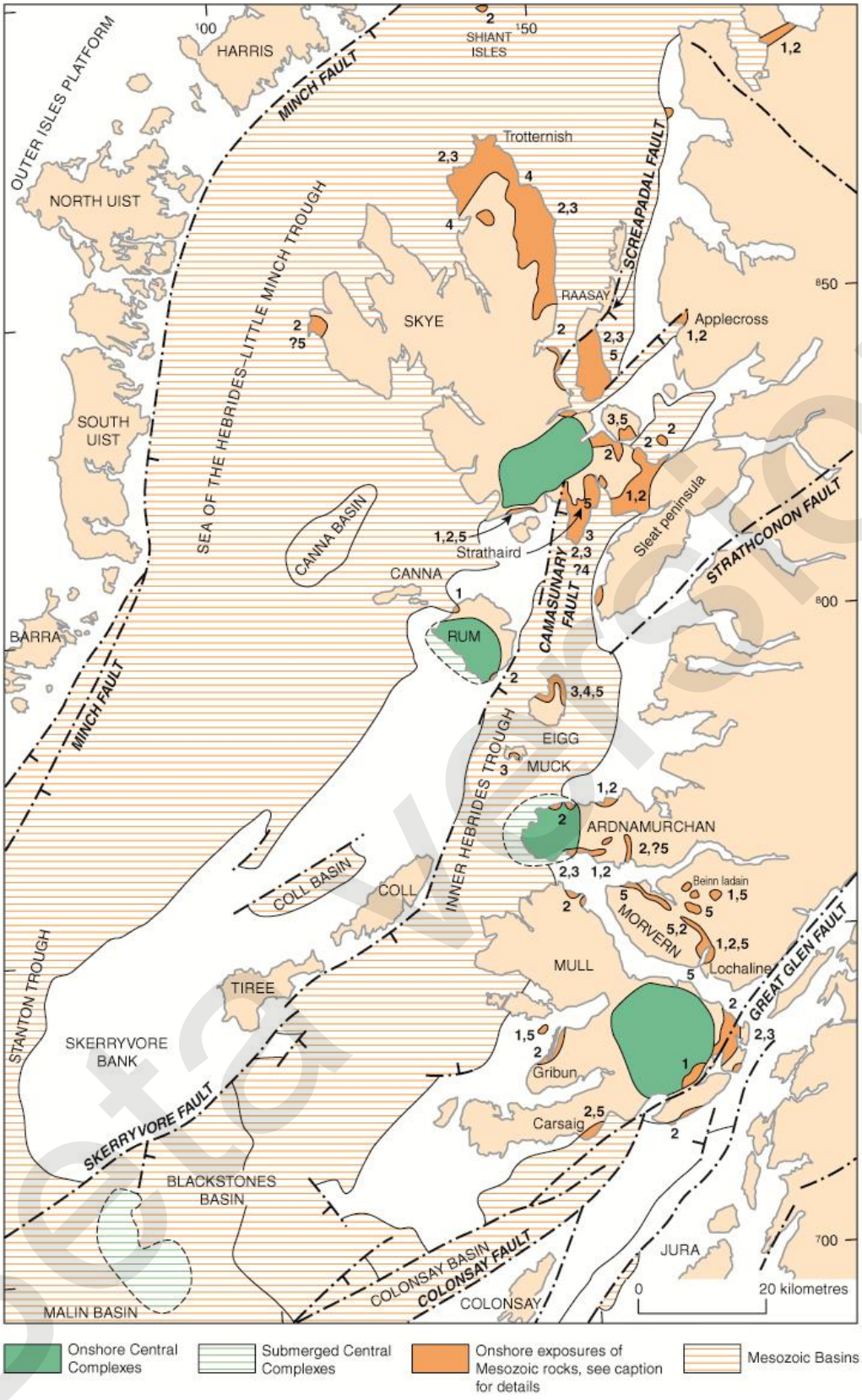


Figure 3-1: Simplified geological map of the Inner Hebrides showing the location of Mesozoic basins, the location where Mesozoic rocks occur onshore, and the locations of the Paleocene central complexes. Pre-Mesozoic rocks are uncoloured (after Fyfe *et al.* 1993). The Camasunary Fault most likely links to the Skerryvore Fault. 1, Permo-Triassic; 2, Lower Jurassic; 3, Middle Jurassic; 4, Upper Jurassic; 5, Upper Cretaceous.

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3.2 Triassic

3.2.1 Introduction

Many of the New Red Sandstone (NRS) occurrences detailed below are assigned to the Triassic on the grounds of lithology, unconformable relationships with older rocks (Chapter 2), or a conformable one with overlying, fossiliferous Jurassic strata. Fossils are rare in all but the highest of these sequences. In the Hebridean area, the New Red Sandstone sequences are thought to belong to the Upper Triassic and accumulated during the earliest stages of basin formation (Steel 1974a, b; Steel *et al.* 1975).

3.2.2 Arran

The Lamlash Sandstone and Glen Dubh Sandstone formations (Figure 3-2) are well exposed on the coast on the east side of the island. These sandstones are massive, reddish to purple, and are stratigraphically continuous with the underlying Permian sandstones (Figure 3-3). The Permian–Triassic boundary is difficult to identify here, as it is elsewhere in Great Britain, and is arbitrarily located within the sandstones of the Sherwood Sandstone Group (Warrington *et al.* 1980).

System	Formation	Thickness (m)	UK-wide group
TRIASSIC	Westbury*	?	Penarth
	Derenenach Mudstone*	?	Mercia Mudstone
	Levencorroch Mudstone	c. 80	
	Auchenhew Mudstone	c. 200	
	Lag a'Bheith		
	Glen Dubh Sandstone	c. 400	Sherwood Sandstone
	Lamlash Sandstone		
	Machrie Sandstone		
PERMIAN	Brodick Beds, including:		
	Brodick Breccia	c. 740	
	Corrie Sandstone	c. 500	
	volcanic rocks near base		

* found only as blocks in the Central Arran Ring-complex

Figure 3-2: Permian and Triassic strata, Isle of Arran.

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Figure 3-3: Interbedded conglomerates and sandstones of the Lamlash Sandstone Formation, Claughlands Point, Lamlash Bay, east Arran. Pole *ca*. 1 m long.

The Permian and Triassic rocks of Arran were considered virtually devoid of stratigraphically diagnostic fossils until the discovery of Triassic miospores (Warrington 1973) in what is now termed the Lag a' Bheith Formation (Lovell 1991). This formation comprises mudstones with fine-grained sandstones and contains carbonate concretions, resulting from evaporation under subaerial conditions.

The overlying Auchenhew Mudstone Formation covers much of south Arran and corresponds with the areas shown as Triassic on published maps (Figure 3-4; Figure 3-5; Figure 3-6). It extends from Largybeg Point in the east, to Drumadoon in the west, and there are abundant, excellent exposures on the foreshore, in cliffs and in many stream and river sections. The formation comprises a succession of fine-grained sandstones, mudstones and calcareous mudstones (marls) that has been equated with the Mercia Mudstone Group (Lovell 1991). The presence of carbonate concretions, pseudomorphs after halite, ripple marks and desiccation cracks indicate that the beds formed mainly under shallow-water conditions, but with periods of drying out and deeper flooding.

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Figure 3-4: Mudstones of the Auchenhew Mudstone Formation, Auchenhew Woods, (below road), south Arran. Pole *ca.* 1 m long.



Figure 3-5: Variegated mudstones in the Auchenhew Mudstone Formation, Auchenhew Woods, (below road), south Arran. Pole *ca.* 1 m long.



Figure 3-6: Interbedded mudstones, siltstones and sandstones of the Auchenhew Mudstone Formation at the waterfall on the Levencorroch Burn, between the road and the coast, south Arran.

Mudstones, siltstones, and fine micaceous sandstones of the Levencorroch Mudstone Formation are exposed in stream sections near Levencorroch Hill (Figure 3-7). These beds also contain carbonate concretions.



Figure 3-7: Interbedded mudstones, siltstones, and fine micaceous sandstones of the Levencorroch Mudstone Formation in stream section at Levencorroch Hill, south Arran. Uppermost unit is a Paleocene sill with vertical columnar joints.

Preview version

The highest parts of the Triassic succession occur only as downfaulted blocks in the Paleocene Central Arran Ring-complex (Chapter 9) (Warrington *et al.* 1980). There, they are exposed in the Allt nan Dris, where mudstones of the Levencorroch Mudstone Formation are associated with grey-green siltstones of the Derenenach Mudstone Formation. The latter closely resemble the 'tea green marls' of the Collin Glen Formation at the top of the Triassic succession in Northern Ireland. Overlying black mudstones with thin limestones have yielded marine bivalves (e.g. *Rhaetavicula contorta, Chlamys valonensis, Protocardia philipiana?, Modiolus minimus?*) and these beds have been assigned to the Westbury Formation of the Rhaetian Penarth Group. Clasts of Moine rocks (psammite and pelite), cherty fossiliferous limestone (Cambro-Ordovician, Durness Group), red feldspathic sandstone (Torridonian), vein-quartz, quartzite, granite and rare, red andesitic porphyry (?Siluro-Devonian) (Chapter 2) indicate both local and distal provenance for these beds.

3.2.3 Mull

Up to 60 m of conglomerates, sandstones and calcretes occur at Gribun and on Inch Kenneth off western Mull, where a striking angular unconformity with the underlying Moine Supergroup rocks (Chapter 2) is exposed on the foreshore and in cliff sections (Figure 3-8; Figure 3-9; Figure 3-10; Figure 3-11).



Figure 3-8: Inch Kenneth from Beinn na h-Iolaire, west Mull. View towards the NW.



Figure 3-9: The southern part of Inch Kenneth from Beinn na h-Iolaire, west Mull. View towards the NW.

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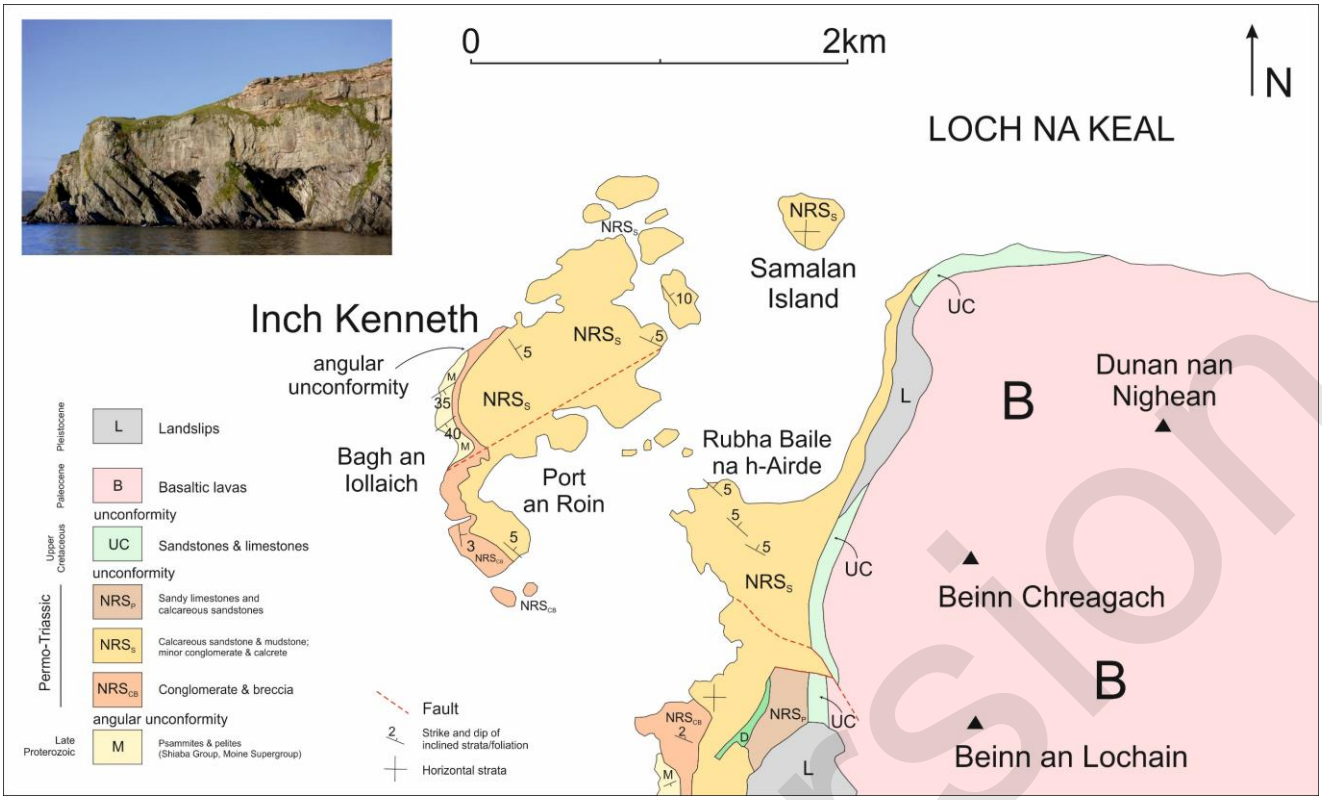


Figure 3-10: Simplified geological map of the Inch Kenneth – Gribun area, west Mull.



Figure 3-11: Triassic-Moine angular unconformity, west coast of Inch Kenneth.

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Upper Triassic miospores have been recovered from beds near to the top of the Gribun succession that also contain indistinct bivalve remains. The uppermost beds are sandy limestones of Rhaetian age, which contain fish scales and bivalves (e.g. *Cardinia* sp., *Chlamys valoniensis*, *Protocardia rhaetica*, *Rhaetavicula contorta*).

In eastern Mull, Triassic conglomerates and sandstones are exposed in the cores of the anticlines that surround the Paleocene central complex, from Craignure to Loch Don and Loch Spelve. In addition, there are extensive sandstone outcrops on the west shore of Loch Spelve, which extend up Glen Lussa, where the Triassic rocks occur in screens (remnants of country-rock) between inclined basic sheets (Chapter 9). Clasts in the conglomerates are mainly quartzite and vein-quartz, although pebbles of Moine rocks are abundant locally where these lithologies are *in situ* nearby. Small outcrops of Triassic strata are also found within the central complex, where their steep dips indicate considerable disturbance by the Paleocene intrusions.

3.2.4 Morvern

Up to 100 m of conglomerates, sandstones, calcareous mudstones, mudstones and calcretes are present beneath younger Mesozoic rocks and Paleocene lavas, and in outliers to the north of the lavas. Clasts in the conglomerates are from local Moine rocks and Caledonian felsic minor intrusions. Thicknesses are very variable. The Triassic beds appear to be absent to the west of Loch Teacuis, and even in the vicinity of Loch Aline and Inninmore Bay, where the thickest and most complete sections have been measured. Lee & Bailey (1925) identified rocks of possible Rhaetian age at Inninmore.

3.2.5 Ardnamurchan

Sandstones, calcretes and sedimentary breccias crowded with locally derived Moine psammite, pelite and vein-quartz fragments underlie Paleocene lavas on the east side of Ben Hiant (Figure 3-12). Similar rocks, with abundant caliche, crop out on the south coast at Mingary and underlie Lias beds on the north coast at Ockle Point and at Swordle.



Figure 3-12: Non-fossiliferous Triassic sandstones unconformably overlying Moine Supergroup psammites and pelites, SE side of Ben Hiant, Ardnamurchan.

Pre-publication version

3.2.6 Rum

The Monadh Dubh Sandstone Formation of NW Rum is *ca*. 80 m thick and consists of a fining-upwards sequence of sedimentary breccias, conglomerates, caliches and sandstones with thin silty sandstones containing plant remains (Figure 3-13). These NW-dipping beds unconformably overlie Torridonian sandstones (Chapter 2), which have been permeated and replaced by caliches. Clasts in the breccias and conglomerates were generally derived from the nearby Torridonian sandstones, although quartzite pebbles may have come from the basal Cambrian rocks of Skye. Near the middle of the succession, conglomerate-sandstone-caliche cyclothems suggest a change from initial debris flows to fluvial deposition and soil formation. A general change from continental conditions to non-marine shallow-water and estuarine deposition is indicated by the upward progression from fine-grained siltstones and calcareous sandstones with abundant plant and wood fragments, to beds containing fish scales and teeth, and conchostracan arthropods (*Euestheria minuta*). The uppermost beds may correlate with the Mercia Mudstone (Triassic) or Penarth (Rhaetic) groups of England and Wales.



Figure 3-13: Basal Triassic calcretes unconformably overlying and permeating Torridonian Supergroup strata, NW coast of Rum, *ca*. 1 km north of Glen Shellesder. [Photograph courtesy of Henry Emeleus]

Revision

3.2.7 Skye

On Skye, a thin, impersistent development of conglomerates, sandstones and calcretes (caliches or 'cornstones'), attributed to the Stornoway Formation, occurs stratigraphically below the Lower Jurassic rocks near Broadford and on either side of the shallow syncline of Jurassic rocks between Broadford and Loch Eishort (Figure 3-14; Figure 3-15 ; Figure 3-16; Figure 3-17). Similar lithologies crop out east of An Leac on the north side of Soay Sound (Figure 3-18; Figure 3-19).

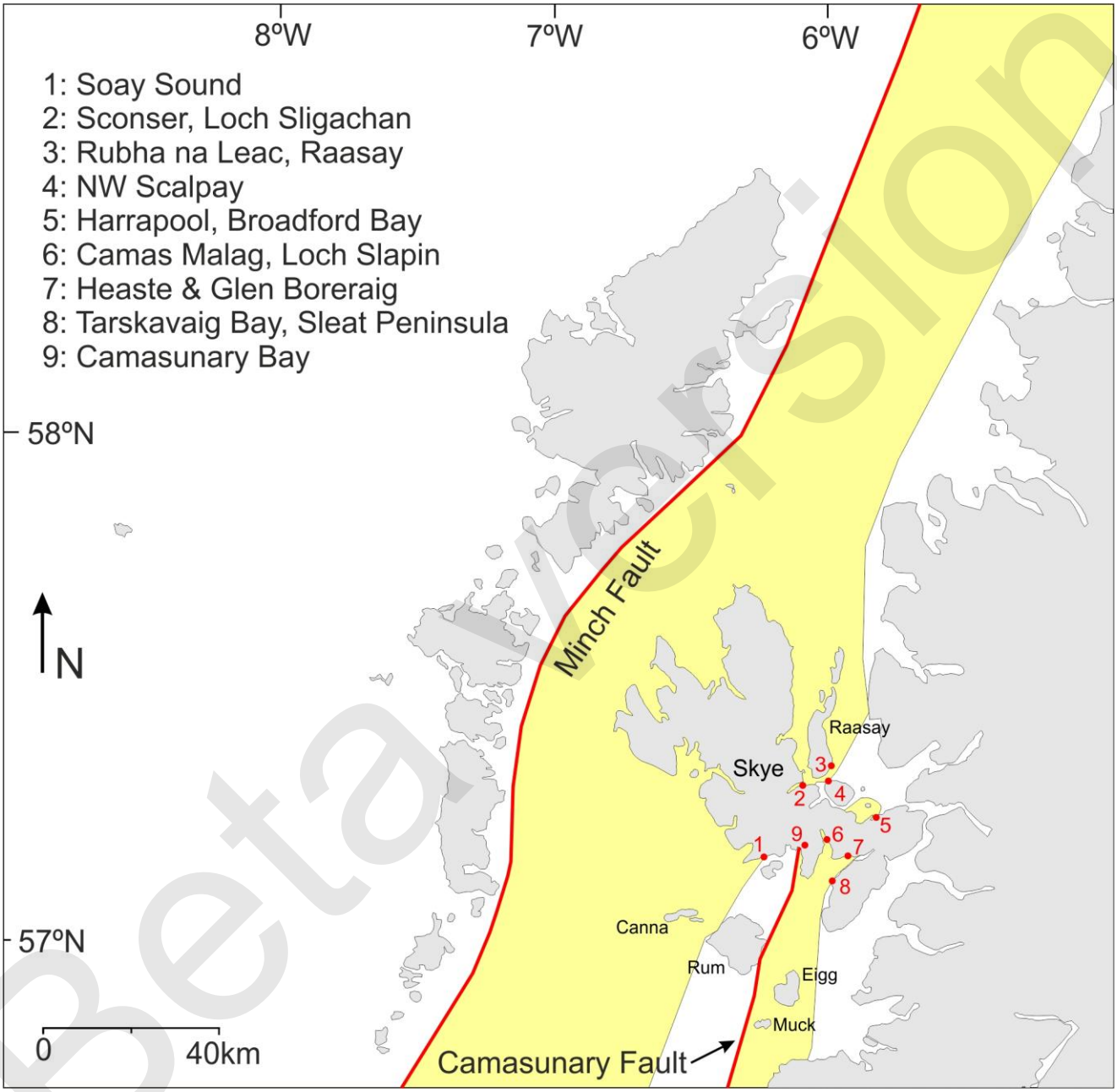


Figure 3-14: Outcrop locations for Triassic strata on Skye and Raasay.

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Figure 3-15: Clint and gryke weathering of Triassic breccia, south side of the Allt nan Leac, Strath, Skye. Pole *ca*. 1 m long.



Figure 3-16: (a) Triassic conglomerate/breccia, comprising cobbles and pebbles of Cambro-Ordovician Durness Group dolostone (which unconformably underlie these strata) in a red, calcareous, sand- to silt-grade matrix, in the upper part of the Allt nan Leac valley in Glen Boreraig (south of Beinn an Dubhaich), Strath; pole *ca*. 1 m long; and, (b) detail of breccia, hammer *ca*. 30 cm long.



Figure 3-17: Triassic conglomerate/breccia, dominated by pale cobbles and pebbles of off-white quartz arenite/sandstone (Cambrian 'quartzite'), Cambro-Ordovician dolostone, and uncommon red-brown feldspathic arenite ('Torridonian'), adjacent to track on the west side of the valley of the Allt na Pairte, north of the abandoned village of Boreraig, Strath. Pole *ca.* 1 m long.

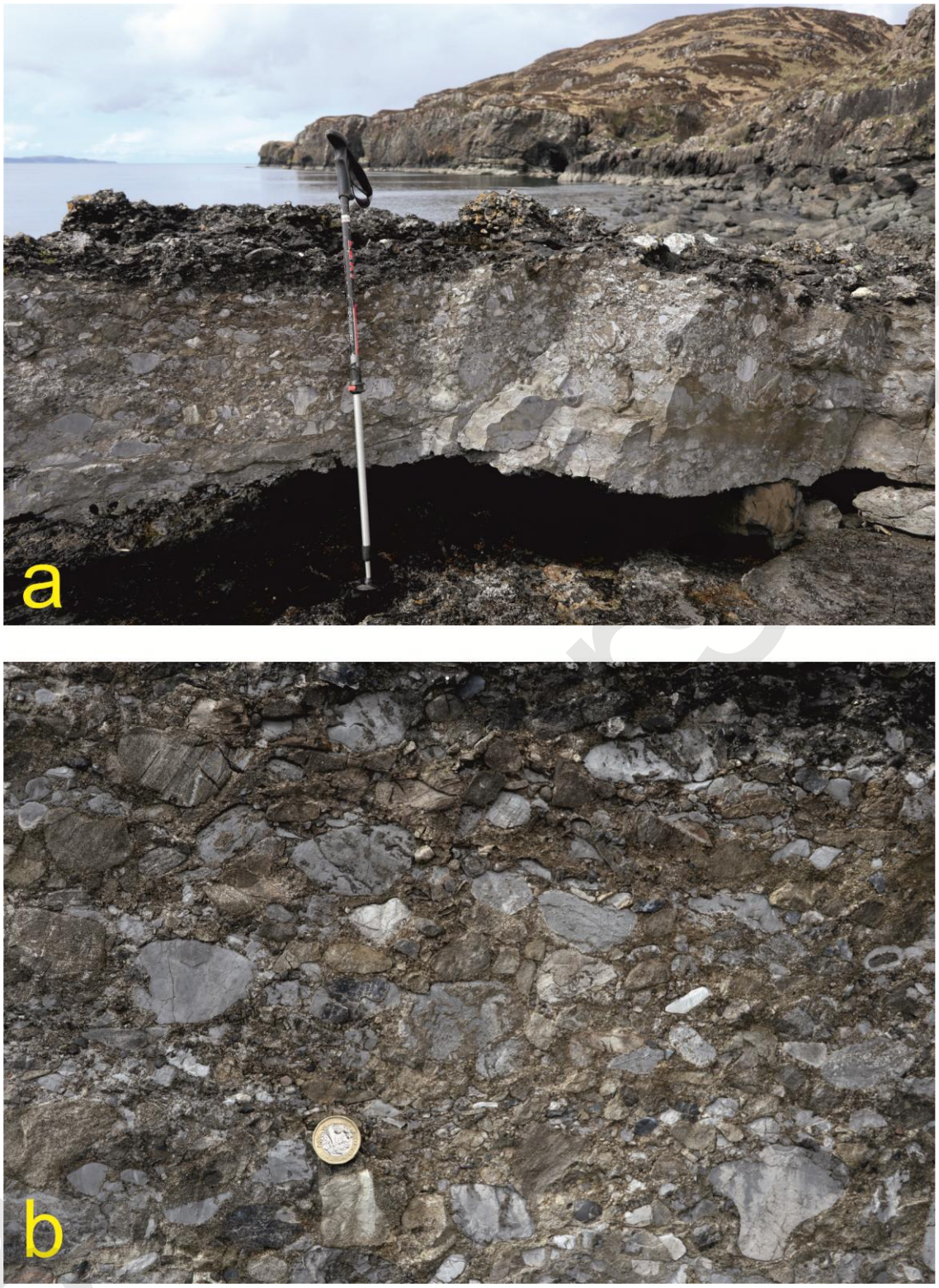


Figure 3-18: (a) Triassic strata, predominantly matrix-supported conglomerates and sandstones, An Leac, north side of Soay Sound, south Skye, view towards the west, pole *ca.* 1 m long; and, (b) detail of Triassic alluvial fan conglomerate, dominated by pale cobbles and pebbles of Cambro-Ordovician dolostone and uncommon pebbles of off-white quartz arenite/sandstone (Cambrian 'quartzite'), and red-brown feldspathic arenite ('Torridonian'), coin *ca.* 24 mm across.



Figure 3-19: Detail of Triassic alluvial fan conglomerate, dominated by pale cobbles and pebbles of Cambro-Ordovician dolostone and uncommon pebbles of off-white Cambrian quartz arenite/sandstone ('quartzite'), and red-brown feldspathic arenite ('Torridonian'). Coin *ca*. 24 mm across.

Poorly exposed, faulted strips of Mesozoic rocks, including Triassic strata, occur on the northern slopes of Glamaig, south of Loch Sligachan, where they have been considerably disturbed by the intrusion of Paleocene granites (Chapter 9). Pebbles and other clasts in the Triassic conglomerates are of local derivation and are predominantly of Torridonian sandstone, Cambro-Ordovician dolostone, chert and, less commonly, Cambrian 'quartzite'.

In NW Scalpay, at Eilean Leac na Gainimh and Rubh' a' Chinn Mhòir, *ca*. 50 m of conglomerates unconformably overlie Torridonian strata and dip at *ca*. 30° towards the NW. The clasts within the conglomerates include Torridonian sandstone, Cambro-Ordovician sandstone/quartzite and dolostone, (rare) Lewisian gneiss, and vein quartz.

At Tarskavaig on the west side of Sleat, an outcrop of Triassic conglomerates unconformably overlies Torridonian strata and is located (inland) *ca*. 600 m NE of Tarskavaig Bay. Clast lithologies include: pink-stained Cambro-Ordovician sandstone/quartzite and dolostone; Torridonian sandstone; and, red and black (Cambro-Ordovician) chert, all set in a matrix that ranges between a medium- to coarse-grained sand(stone) and a limestone. Of note, the nearby Torridonian strata are disrupted by fractures/fissures that are filled with (? Triassic) carbonate. The skerries of Sgeir Fhada and Sgeir Biodaig in Tarskavaig Bay are formed of similar conglomerates.

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3.2.8 Raasay

There are several occurrences of the Stornoway Formation in the southern part of Raasay. These outcrops are much faulted and are obscured towards the NE beneath the immense slipped mass of Jurassic rocks at Beinn na Leac, reappearing beyond the landslip at Rubha na Leac. At the latter, is an informative *ca*. 40 m thick sequence illustrating the complexity of the Triassic depositional system (Figure 3-20; Figure 3-21; Figure 3-22; Figure 3-23; Figure 3-24; Figure 3-25; Figure 3-26; Figure 3-27; Figure 3-28; Figure 3-29).

The coarse-grained lithologies, typically poorly sorted sheet-like breccias and conglomerates, formed as aprons in an alluvial fan system and contain a wide range of clast lithologies, including basement gneiss (Lewisian Gneiss Complex), Late Proterozoic ('Torridonian') sandstone and siltstone, and Lower Palaeozoic (Cambro-Ordovician) dolostone and sandstone ('quartzite') (neither seen *in situ* on Raasay). Where the clasts are angular (i.e. typical of a breccia) and lack a support framework and 'float' in a fine-grained (silt to mud grade) red-brown matrix, they are, most likely, the product of a mudflow mechanism of transport. Where the clasts are more rounded (i.e. typical of a conglomerate) and form a touching framework, with interbedded cross-stratified sandstones, they are, most likely, the product of a high energy stream flood mechanism of transport.

Rarer finer-grained lithologies, sandstone, siltstone and mudstone, formed in a floodplain system and range between cross-stratified pebbly sandstones typical of a braided river system, and laminated siltstones/mudstones deposited from suspension in the overbank environment.

Distinctive brown-orange calcretes (concretionary carbonate deposits; carbonate-cemented soils) are analogues to present-day caliches, formed in a semi-arid (terrestrial) floodplain environment. Various textures, including breccia, pisolitic (concretionary grains) and laminated facies, indicate they formed during diagenesis at or near to the (Earth's) surface by downward-percolating surface water, with the development of non-tectonic fractures. At their simplest, the calcretes comprise an accumulation of authigenic carbonate, i.e. nodules, angular masses ('breccia'), sheets and pipes, that have formed *in situ*. Where the calcrete has a brecciated appearance, the texture can be attributed to minor amounts of disruption or rotation of the secondary carbonate (i.e. essentially formed *in situ*). The host to this carbonate can be any of the other lithologies outlined above, although typically the finer-grained material (sand and silt grade). The carbonate typically fills pore space (more common deeper in the profile) or partially replaces original grains (shallower in the profile). The pisolitic variant typically occurs as laminae or bands of coated grains and is typically silicified. In any one bed, the amount of carbonate typically increases towards the top. The source of the carbonate can be attributed to wind-borne, fine-grained sediment (loess) or dissolved in rainwater. With time, the carbonate front migrates downwards. Calcretes can be polygenetic, forming in discrete episodes. Laminated variants form when downward percolation is inhibited. Intermittent sedimentation can occur during calcrete formation.

Within the sequence at Rubha na Leac, the following generalisations can be made: the sequence is close to horizontal, best defined by the sandstones; the interleaved character of the sequence, dominated by conglomerates and sandstones, indicates periodic changes in the depositional environment at any one location within the system; the conglomerates formed within a high-energy braided stream system; clast size is variable, with the largest up to 30 cm across; clast-supported textures are common; the dominant clast lithologies are of Torridonian sandstone and siltstone, Cambro-Ordovician sandstone ('quartzite') and dolostone, with material from the Lewisian Gneiss Complex and the Moine Supergroup (mainly schist) much less common; up-sequence the amount of conglomerate lessens and there is a concomitant increase in the amount of sandstone/calcrete; the carbonate-dominated soil-forming (pedogenic)

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calcretes are best developed in the floodplain sandstones; Paleocene intrusions, including a prominent dyke, cut these strata and, of interest, cannot be traced across the fault to the south, the Beinn na Leac Fault, that defines the Beinn na Leac Landslip.



Figure 3-20: Triassic (New Red Sandstone) Stornoway Formation conglomerates, sandstones, siltstones and calcretes of Rubha na Leac, SE Raasay.



Figure 3-21: Triassic (New Red Sandstone) Stornoway Formation conglomerates, sandstones, siltstones and calcretes of Rubha na Leac, SE Raasay.

Preview



Figure 3-22: Poorly sorted lensoid bodies of conglomerate with interbedded discontinuous layers of red sandstone, Rubha na Leac, SE Raasay. Pole *ca*. 1 m long.



Figure 3-23: A pale laminated pebbly channel sandstone overlain by unsorted beds of conglomerate separated by a layer of red sandstone containing cobbles. Rubha na Leac, SE Raasay. Ruler 30 cm long.



Figure 3-24: Bedding surface with close-packed, randomly oriented cobbles and angular fragments of pale Cambro-Ordovician sandstone/quartzite, coarse- to medium-grained red ('Torridonian') sandstone, and pale (inweathered) Cambro-Ordovician dolostone, all set in a pale, coarse, sand matrix. Rubha na Leac, SE Raasay. Ruler 30 cm long.



Figure 3-25: Bedding surface with close-packed, randomly oriented cobbles and angular fragments of pale Cambro-Ordovician sandstone/quartzite, coarse- to medium-grained red ('Torridonian') sandstone, banded gneiss (top centre), and pale (inweathered) Cambro-Ordovician dolostone, all set in a pale, coarse, sand matrix. Rubha na Leac, SE Raasay. Ruler 30 cm long.

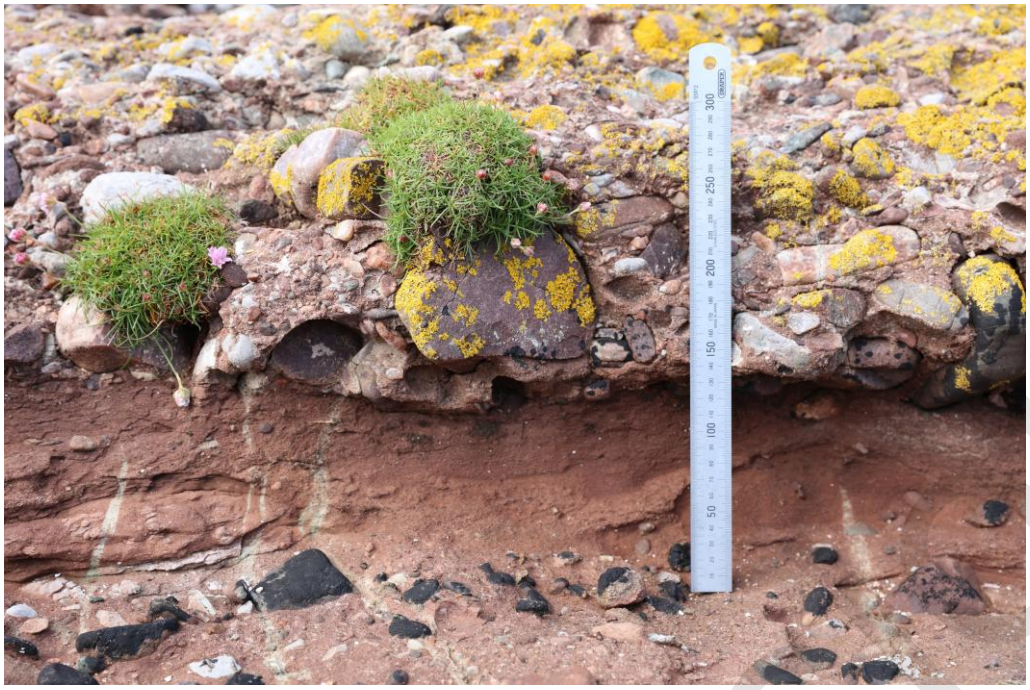


Figure 3-26: Brown-orange (authigenic) carbonate-dominated calcrete with diffuse veins of less oxidised material, overlain by very poorly sorted conglomerate dominated by close-packed, randomly oriented cobbles and angular fragments of pale Cambro-Ordovician sandstone/quartzite and coarse- to medium-grained red ('Torridonian') sandstone. The calcrete matrix is medium to coarse sand grade. Rubha na Leac, SE Raasay. Ruler 30 cm long.

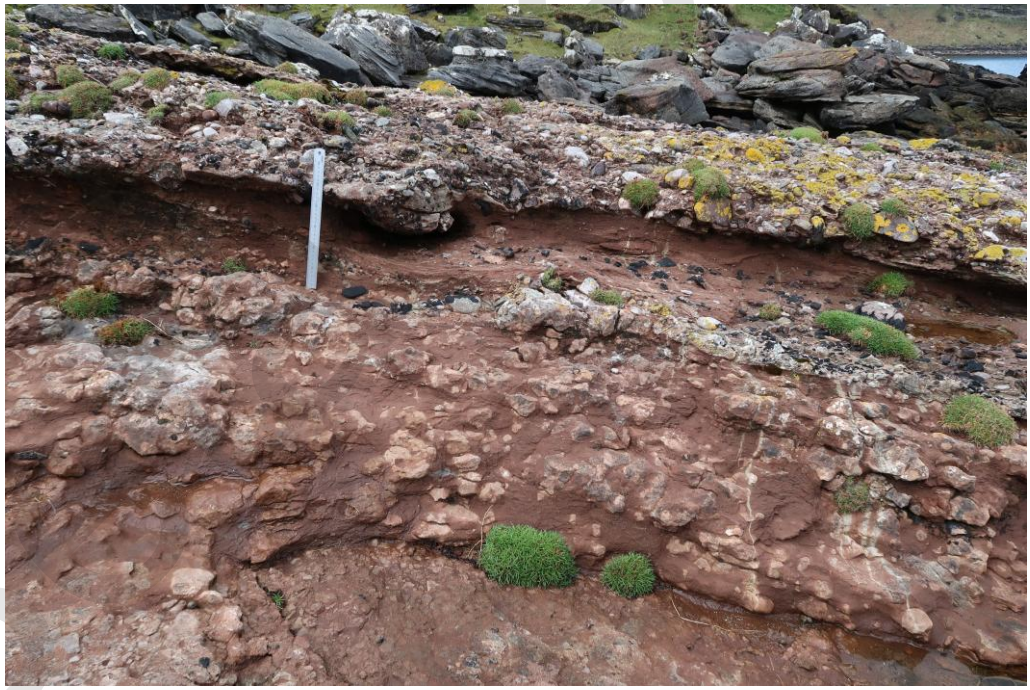


Figure 3-27: Brown-orange (authigenic) carbonate-dominated calcrete with breccia-like texture and diffuse veins of less oxidised material, grading up into a laminated variant with dispersed cobbles; locally the cobbles form discrete thin layers. The calcrete matrix is medium to coarse sand grade. Overlying the calcrete, with a sharp contact, is a very poorly sorted conglomerate dominated by close-packed, randomly oriented cobbles and angular fragments of pale Cambro-Ordovician sandstone/quartzite and coarse- to medium-grained red ('Torridonian') sandstone. Rubha na Leac, SE Raasay. Ruler 30 cm long.

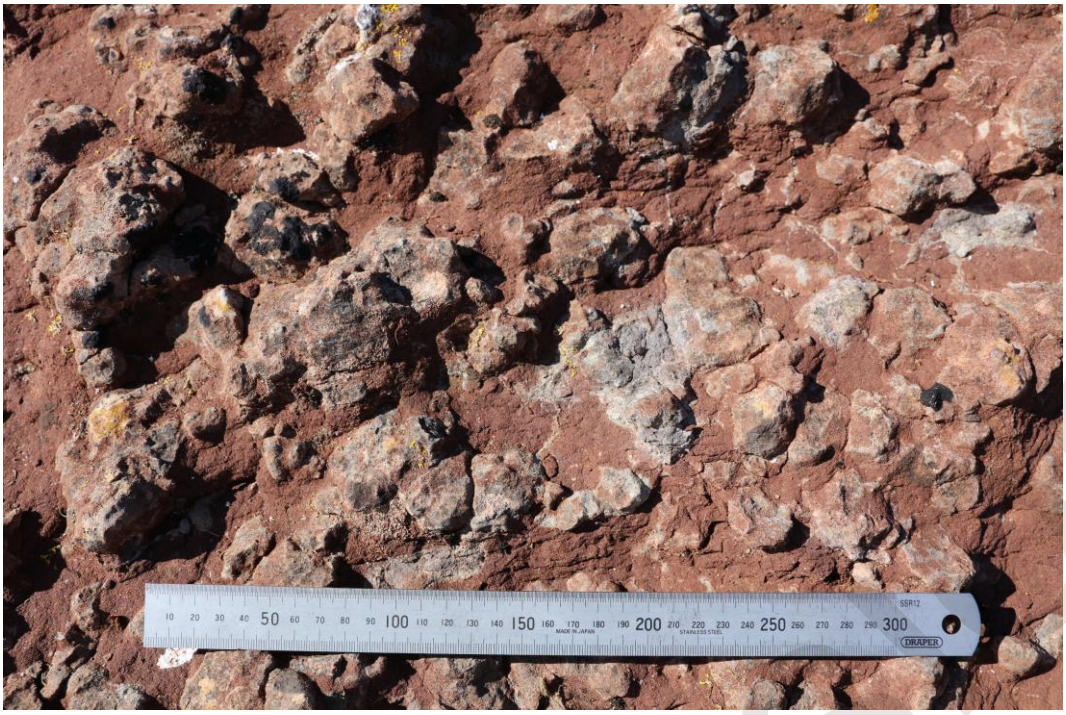


Figure 3-28: Brown-orange (authigenic) breccia facies calcrete with randomly oriented angular fragments of pale (less oxidised) material in a more oxidised medium to coarse sand grade matrix. Rubha na Leac, SE Raasay. Ruler 30 cm long.



Figure 3-29: Brown-orange (authigenic) breccia facies calcrete with randomly oriented angular fragments of pale (less oxidised) material in a more oxidised sand grade matrix. Note the left-of-centre pale 'fragment' with a preserved thin (*ca.* 1 cm) layer of coarse sandstone, and the irregular (anastomosing) boundaries between the pale and darker (more oxidised) materials. Rubha na Leac, SE Raasay. Ruler 30 cm long.

Three outcrops of coarse, poorly bedded breccia, *possibly* of Triassic age, occur in north Raasay: at Brochel; on the unnamed hill NW of Brochel; and, NW of Loch an Uachdair (Figure 3-30).



Figure 3-30: Outcrops of breccia of (possible) Triassic age, Brochel, north Raasay.

The sub-circular outcrop of breccia below Brochel Castle measures *ca*. 75 m across and is surrounded by Late Proterozoic ('Torridonian') dark grey, fissile mudstones and siltstones of the Brochel Member (Diabaig Formation), which dip at *ca*. 15° towards the west (Chapter 2) (Figure 3-31; Figure 3-32; Figure 3-33; Figure 3-34). The irregular contact of this breccia with the Brochel Member strata is exposed on the north side of the crags. The centre of the breccia outcrop is poorly exposed within a depression. The breccia is essentially unstratified and dominated by angular to sub-rounded cobbles and boulders, the latter rarely up to 1 m across, of rusty-brown, coarse-grained sandstone very similar to the strata of the Leac-stearnan Member of the Applecross Formation (Figure 3-34), which crops out *ca*. 300 m to the west. The breccia matrix is dominated by silt and mud grade material, with a pale, heterogeneously-distributed carbonate cement. Of significance, there are no clasts of material from the Lewisian Gneiss Complex, which is exposed a short distance to the north and forms most of north Raasay.



Figure 3-31:The Brochel Castle breccia outcrop, Raasay.

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Figure 3-32: The Brochel Castle breccia outcrop, Raasay.



Figure 3-33:Detail of the Brochel Castle breccia outcrop, Raasay.

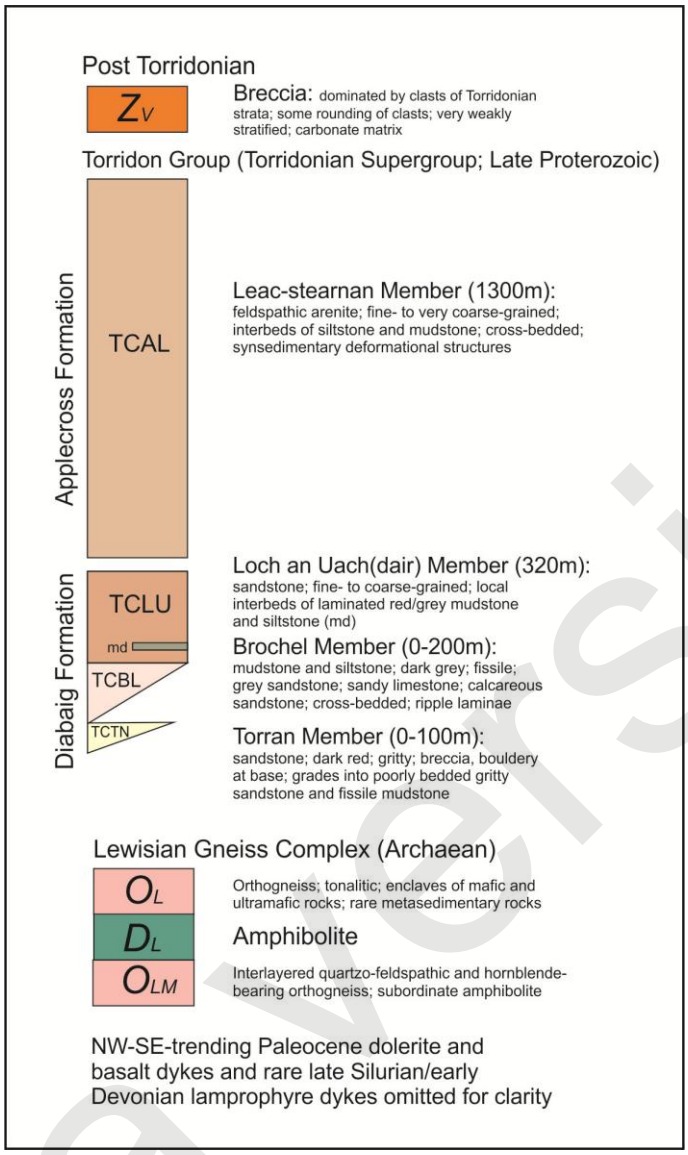


Figure 3-34: Lithostratigraphy of Torridonian strata, north Raasay.

The outcrop on the hillside (Figure 3-30) is the best exposed and most informative of the three breccia masses preserved in north Raasay (Figure 3-35; Figure 3-36; Figure 3-37). It, too, is oval, with a long axis (E-W) length of *ca*. 70 m. Here, the surrounding rocks are part of the Lewisian Gneiss Complex, with Torridonian strata of the Loch an Uach(-dair) Member of the Diabaig Formation unconformably overlying the basement gneiss *ca*. 100 m to the west. As with the Brochel outcrop, the margin of this breccia mass is somewhat angular, apparently controlled by the jointed character of the basement gneisses. The clast population within this outcrop is somewhat different to that at Brochel but, although this breccia mass apparently unconformably overlies the basement gneiss, it, similarly, is absent as a clast lithology.

At the western end of the hillside breccia outcrop, obvious boulder- and cobble-dominated material grades westwards into coherent blocks of stratified shale and sandstone of the Brochel Member of the Diabaig Formation that crops out (i.e. is *in situ*; but is poorly exposed) in the low ground to the south. The dominant well-exposed eastern and southern part of the breccia outcrop is dominated by cobbles and less common boulders of medium- to fine-grained feldspathic sandstones identical to the strata of the

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Loch an Uach(-dair) Member. The matrix is, similarly, of silt and mud grade material, with a pale carbonate cement.



Figure 3-35: The hillside breccia outcrop, NW of Brochel, Raasay. Note apparent dip of the strata towards the east. View is towards the NW.



Figure 3-36: Detail of the middle breccia outcrop, NW of Brochel, Raasay. Three informal units are recognised and comprise lower and upper units dominated by boulders and cobbles of medium- to fine-grained feldspathic sandstones, separated (in the recess) by a breccia dominated by angular, slab-like fragments of grey shale of Brochel Member character. View is towards the NE. Pole *ca.* 1 m long.



Figure 3-37: The NW margin of the hillside breccia outcrop, comprising disrupted slabs of grey shale (Brochel Member) interbedded with breccia of the same material. To the west (left) is *in situ* gneiss. View is towards the NE. Pole *ca*. 1 m long.

A gross stratification to the sequence is recognised, highlighted by the present-day weathering characteristics of the breccia, and clast lithology differences within the outcrop. The lowest and highest of the three obvious units within the outcrop are similar in character and comprise poorly sorted cobble and boulder conglomerate, with dominant clasts of medium- to fine-grained feldspathic sandstones (see above). Between these two units is a breccia dominated by angular slab-like fragments of grey shale of Brochel Member character (Figure 3-34; Figure 3-36). The NW margin of the breccia outcrop is exposed where the middle unit, the breccia dominated by grey shale, is in contact with *in situ* granitic gneiss of the Lewisian Gneiss Complex and is dominated by large slabs of coherent grey shale.

The third breccia outcrop, located NW of Loch an Uachdair, is *ca*. 20 m across and is best exposed on the east side (Figure 3-38; Figure 3-39; Figure 3-40). As with the other two breccia outcrops, the dominant clast lithology of the boulders and cobbles is medium- to fine-grained feldspathic sandstone, identical to the strata of the Loch an Uach(-dair) Member, which, for this breccia outcrop, is the surrounding lithology unit. The surrounding *in situ* exposures of the Loch an Uach(-dair) Member include beds of coarse feldspathic sandstone and grey shale. As with the other two breccia outcrops, the matrix is silt and mud grade material, with a well-developed pale carbonate cement (Figure 3-40).

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Figure 3-38: The unstratified breccia outcrop, NW of Loch an Uachdair. The surrounding Torridonian strata of the Loch an Uach(-dair) Member (Diabaig Formation) are exposed on the left (SE) and right (NW, in shade) side of the mound. In the distance is the escarpment of Paleocene basaltic lavas on the east side of Trotternish on Skye. View is towards the NW.



Figure 3-39: Steep contact between carbonate-cemented breccia and surrounding Torridonian strata of the Loch an Uach(-dair) Member (Diabaig Formation), NW of Loch an Uachdair. Pole *ca*. 1 m long.



Figure 3-40:Detail of carbonate-cemented breccia NW of Loch an Uachdair. Coin *ca.* 24 mm across.

These breccias have previously been interpreted as Paleocene vent infills (Selley 1966). However, the lack of any igneous materials, the fact that Lewisian gneiss fragments are absent, their (poorly-) bedded character, and the presence of an abundant carbonate cement, suggest that they may be interpreted as coarse sedimentary breccias of alluvial fan association and, (only by comparison), of Triassic age.

3.3 Lower Jurassic

3.3.1 Introduction

The Jurassic successions of the Inner Hebrides represent the most complete and best-exposed onshore record of Jurassic sedimentation in Scotland. Preserved mainly on the islands of Skye, Raasay, Mull, Eigg and Muck, together with minor outcrops on the Ardnamurchan peninsula, these strata record deposition in basins (Sea of the Hebrides – Little Minch Trough and the Inner Hebrides Trough) along the north-western margin of the European epicontinental seaway, during a period of progressive rifting that culminated in the opening of the NE Atlantic in the Cenozoic Era. Jurassic rocks are preserved as fault-bounded remnants beneath Paleocene volcanic rocks (Chapter 6) and locally rest unconformably on Triassic or older strata. The Inner Hebrides succession is of international importance for its lithostratigraphic completeness, ammonite (a marine, coil-shelled cephalopod mollusc) -based biostratigraphy and sedimentological detail, providing the principal onshore analogue for offshore Jurassic basins of the Hebridean and West Shetland shelves.

Jurassic subsidence within the Inner Hebrides was driven by post-Variscan thermal relaxation and early rifting, producing a system of shallow marine basins with differential subsidence controlled by structures

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such as the Camasunary–Skerryvore and Minch faults (Figure 3-41; Figure 3-42). Eustatic sea-level changes also played an important role. Basin architecture exerted a first-order control on thickness, facies distribution and stratigraphic completeness. Although Jurassic successions are now fragmented by later uplift, erosion and Paleocene volcanism, the preserved onshore sections provide a coherent record of basin evolution from the Early Jurassic to the Late Jurassic (Figure 3-42).

Thermal alteration of Jurassic strata can be attributed to the Palaeogene magmatic events (Chapters 6-9) but, somewhat surprisingly, is limited, and primary sedimentary features and fossils have survived; only in locations immediately adjacent to the central complexes (Chapter 9) has contact metamorphism obliterated these features.

The Inner Hebrides Jurassic succession spans the Lower Jurassic (Hettangian–Toarcian) to the Upper Jurassic (Oxfordian–Kimmeridgian), with a local development of Callovian strata. The sequence is dominated by marine sandstones, siltstones and mudstones/shales, together with subordinate limestones and ironstones, reflecting deposition on a low-gradient shelf.

The lithostratigraphy is conventionally subdivided into: Lower Jurassic (Broadford Beds Formation up to the Raasay Ironstone Formation); Middle Jurassic (dominated by the Bearreraig Sandstone Formation, the Great Estuarine Group and the Staffin Bay Formation); and, Upper Jurassic (Staffin Shale Formation). This tripartite division can be linked to tectonically controlled extensional events. In the descriptions set out below, based upon basin evolution and deposition environment, it is convenient to deal with the wholly marine Staffin Bay and Staffin Shale formations together in the description of the Upper Jurassic strata (Figure 3-42).

Lower Jurassic strata are best developed on Skye and Raasay, where they comprise a complex succession dominated by abundantly fossiliferous fine-grained sandstones, siltstones and mudstones/shales, together with uncommon but significant limestones and ironstone beds (Figure 3-42). Deposition occurred in a fully marine, open-shelf environment, below storm wave base for much of the time. The succession records relative sea-level fluctuations, expressed as alternations between more argillaceous offshore facies and sandier nearshore deposits. Organic-rich shales/mudstones (Portree Shale Formation) and the distinctive (and economically important, at the beginning of the 20th Century) Raasay Ironstone Formation, locally developed under conditions of reduced bottom-water oxygenation, particularly during the Toarcian, reflecting broader Early Jurassic oceanographic perturbations. Ammonites allow high-resolution correlation with standard NW European zonations.

Middle Jurassic strata are best exposed on Skye, but with key sections on Eigg, are dominated by the thick, tidally-influenced, marine Bearreraig Sandstone Formation, together with the self-evidently named Great Estuarine Group, which records a major shift from open marine sedimentation to restricted marine, lagoonal, deltaic and freshwater environments, reflecting relative sea-level fall and increased sediment supply. Stromatolites indicate deposition in shallow lagoons and lakes and periodic marine incursions are recorded by fossiliferous beds containing bivalves and rare ammonites.

Upper Jurassic strata (*s.l.*) are best exposed in the Staffin area of Trotternish in north Skye, where they form the classic Staffin Bay and Staffin Shale formations. These consist predominantly of dark grey marine mudstones/shales with distinctive carbonate concretions, together with subordinate sandstones and rare limestones, deposited in a relatively deeper marine shelf setting. Ammonite faunas are abundant and diverse, allowing precise correlation with Oxfordian and Kimmeridgian stages. The dominance of fine-grained sediment reflects reduced clastic input and increased accommodation, possibly linked to renewed subsidence during Late Jurassic rifting.

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Sediment supply to the Hebridean Basin during the Jurassic was derived largely from uplifted landmasses to the east and SE. Sandstones are typically quartz-rich, reflecting extensive weathering and recycling. Palaeo-geographically, the Inner Hebrides occupied a position on the north-western margin of the European shelf, with open marine connections to the south and episodic restriction during Middle Jurassic time. Climate during the Jurassic was generally warm temperate to subtropical at a palaeo-latitude of 35-40° N, promoting high levels of biological productivity.

The present distribution of Jurassic rocks in the Inner Hebrides has been strongly influenced by Cenozoic tectonism and volcanism associated with the North Atlantic Igneous Superprovince (NAIS). Extensive Paleocene lava fields cap much of Skye and Mull, protecting underlying Jurassic strata in some areas, while elsewhere removal by erosion has been severe.

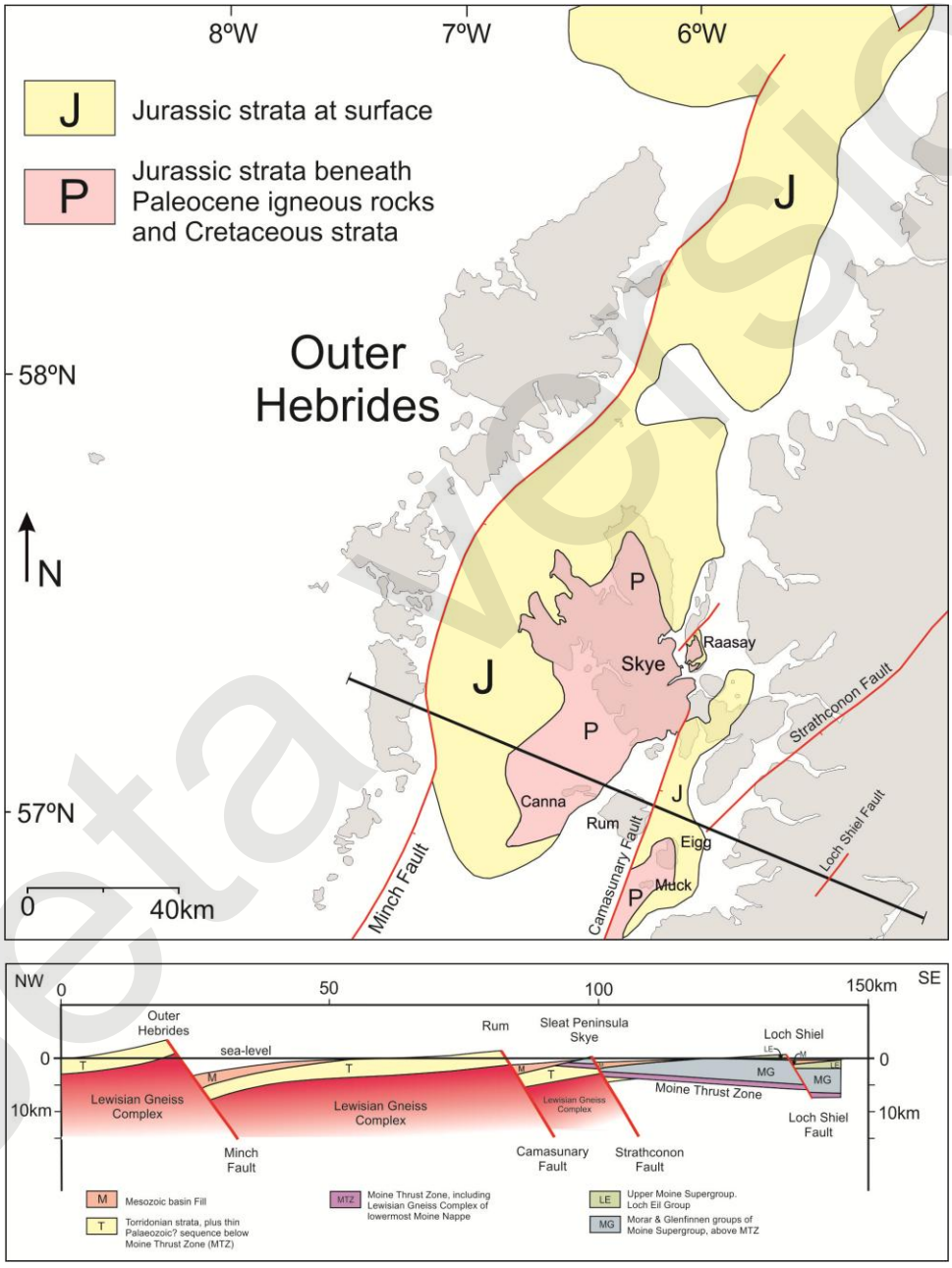


Figure 3-41: Distribution of Jurassic strata on Skye, Raasay and the surrounding area, and a simplified schematic cross-section of Jurassic basin(s) in the Hebrides along line indicated (after Hudson & Trewin 2002).

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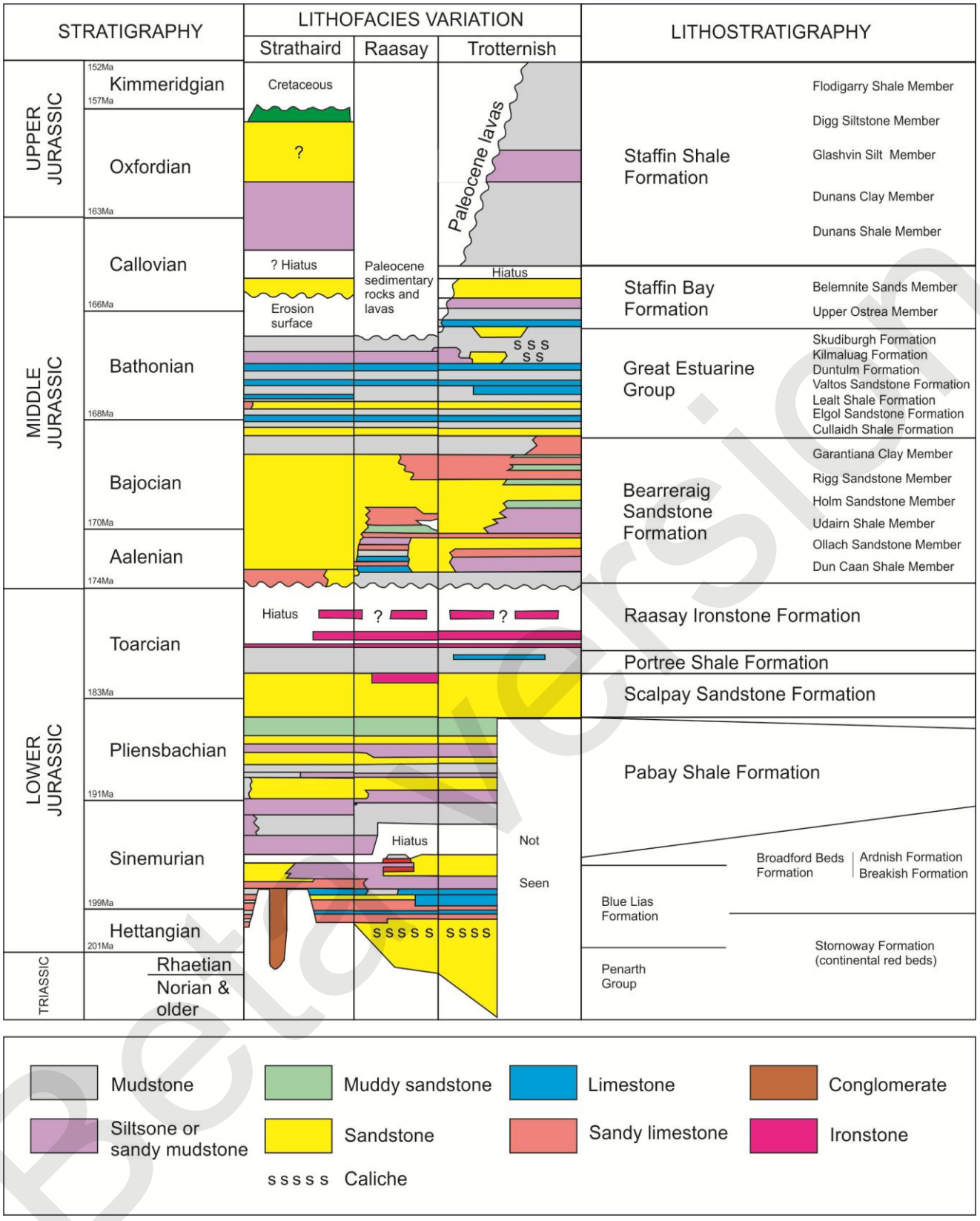


Figure 3-42: Lateral variation in Upper Triassic to Upper Jurassic lithofacies in the Inner Hebrides (based on Morton *et al.* 1987 and Morton 1989).

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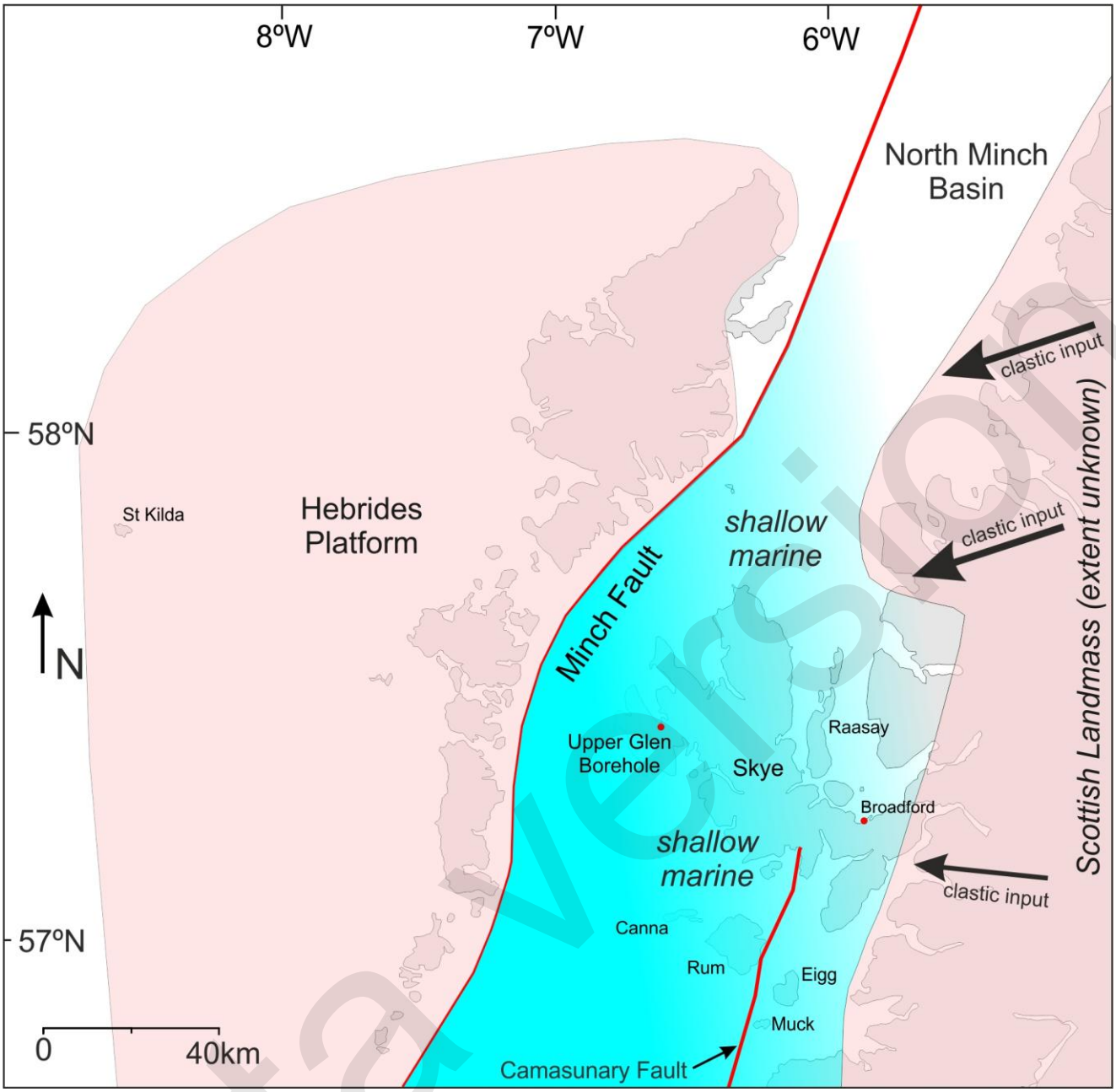


Figure 3-43: Early Jurassic (Pliensbachian) palaeo-geographic map/interpretation (after Hudson & Trewin 2002). The Early Jurassic sediment was derived from the Scottish Mainland, together with the Hebrides Platform, to the west. The thin and calcareous character of the lowermost units, the Breakish and Ardnish formations, imply a low relief to the Scottish Mainland.

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3.3.2 Skye & Raasay

3.3.2.1 Introduction

A wide outcrop of Lower Jurassic strata extends south from Broadford Bay through Strath to Loch Slapin. The oldest part of the Lower Jurassic sequence, the so-called Lower Lias (Morton *et al.* 2024), comprises three formations: Breakish, Ardnish and Pabay Shale (Figure 3-42); the formerly used term, the Broadford Beds Formation, is now split into the Breakish ('Lower Broadford Beds') and Ardnish ('Upper Broadford Beds') formations. The type localities for the Breakish and Ardnish formations are to the east of Broadford, and for the Pabay Shale Formation on the island of Pabay (Figure 3-43; Figure 3-44).



Figure 3-44: Pabay, from south of Broadford, Skye.

Lias rocks crop out on the south side of Scalpay and on the northern slopes of Glamaig, where they have been much disturbed by granites of the Paleocene Western Red Hills Intrusive Centre (Chapter 9). Other outcrops occur to the west of the Camasunary (-Skerryvore) Fault, where the limestones and silty beds are generally thermally altered, and on the north side of Soay Sound.

3.3.2.2 Breakish and Ardnish formations

The type locality Breakish Formation (formerly Lower Broadford Beds) on Skye comprises up to 65 m of marine sandstones, sandy limestones and shales (fissile mudstones) that are underlain by red sandstones in central Skye, which may also be of very early Jurassic (Hettangian) age (Figure 3-45; Figure 3-46; Figure 3-47).

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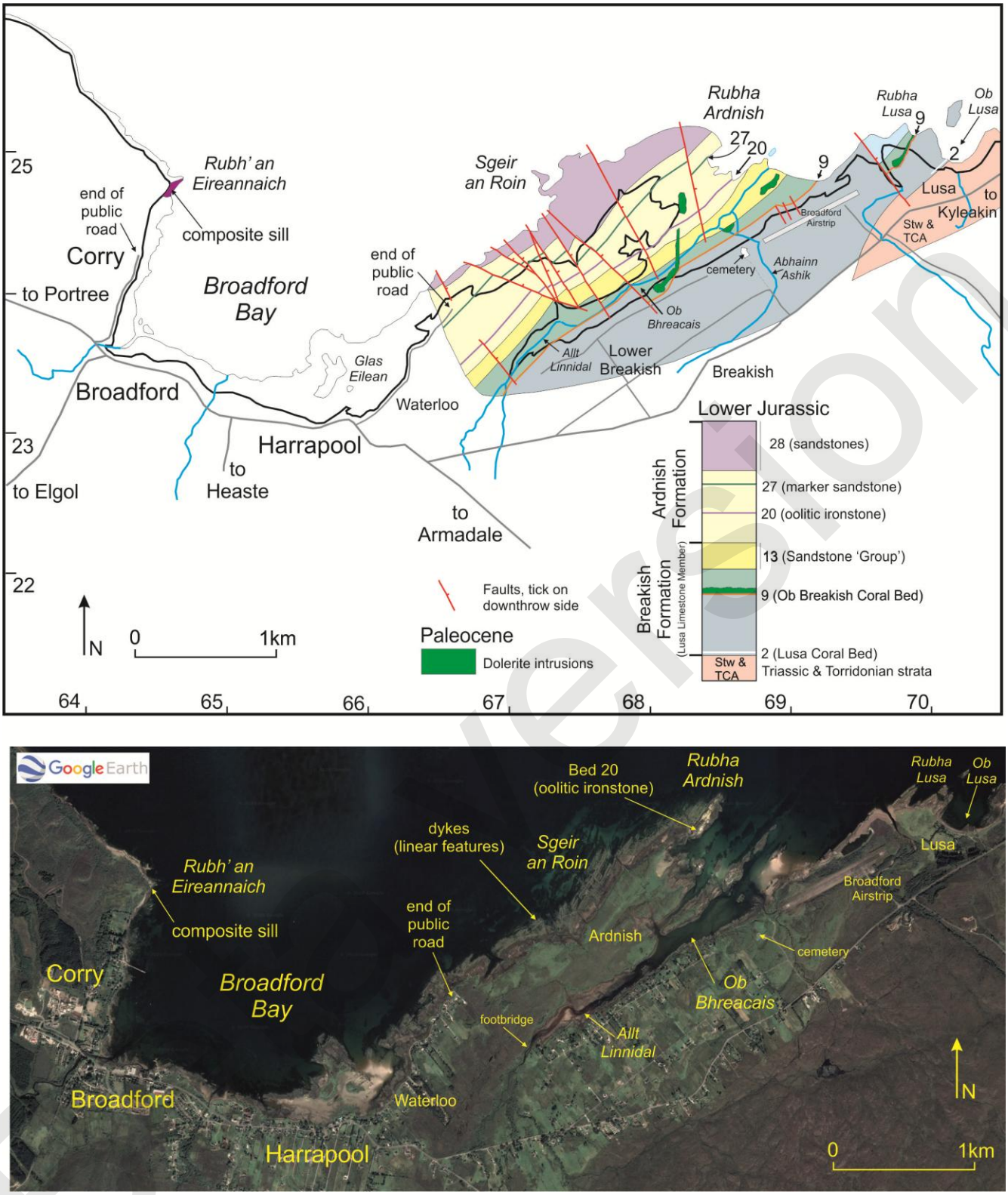


Figure 3-45: Summary map of the Broadford Bay area and annotated Google Earth® image.

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Figure 3-46: Annotated oblique Google Earth® images of the Broadford Bay area.

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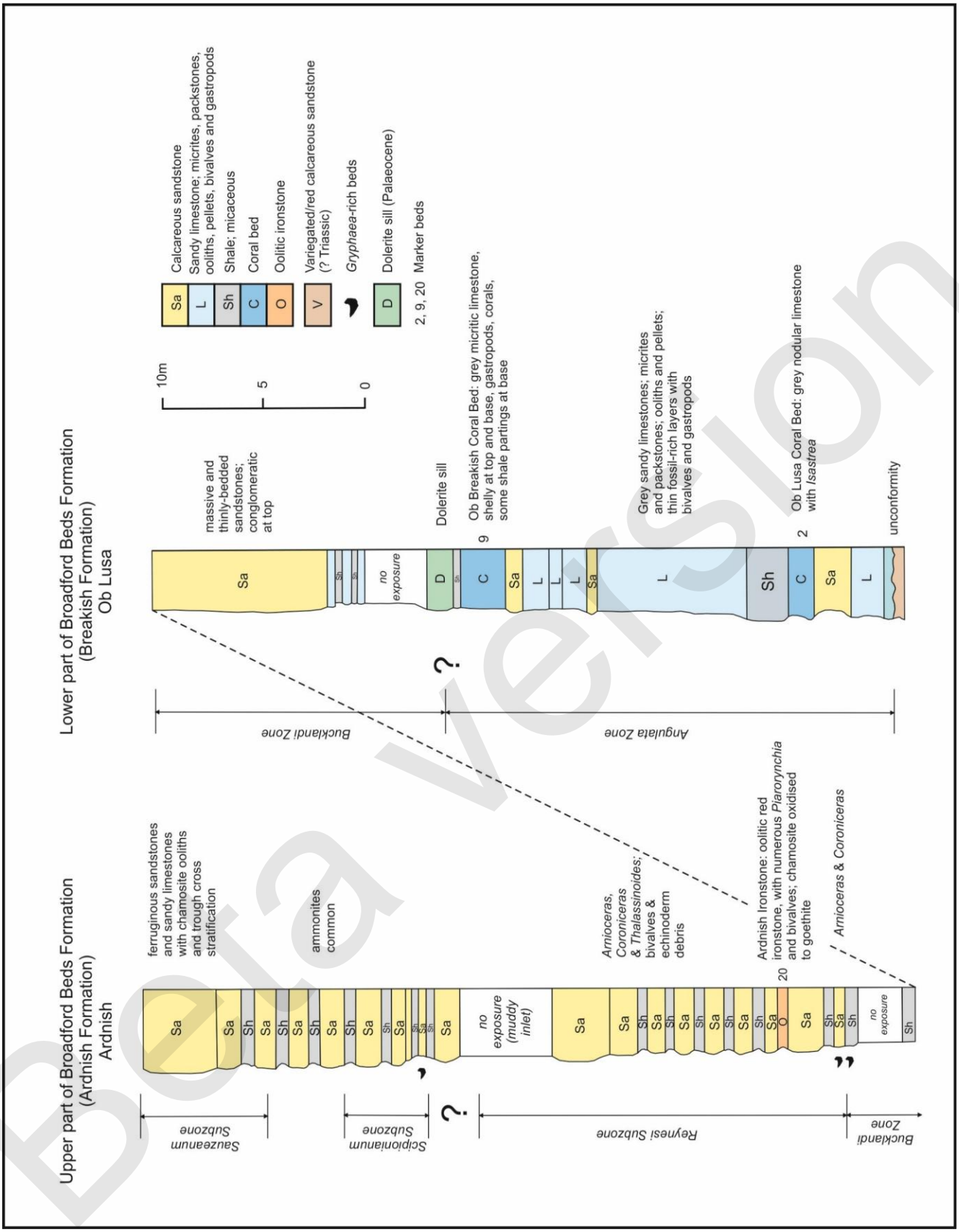


Figure 3-47: Summary stratigraphic log of the Breakish and Ardnish formations, Broadford Bay.

Significant lithostratigraphical units include the Ob Lusa Coral Bed, near to the base of the type-section at Breakish on the east side of Broadford Bay, with compact colonial colonies of the oyster *Liostrea murchisoni,* which formed close to the palaeo-shoreline (Figure 3-48).

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Figure 3-48: Ob Lusa Coral Bed of the Breakish Formation on the west side of Ob Lusa, Breakish. Coin *ca.* 20 mm across.

Approximately 20 m further up the sequence, the (Ob) Breakish Coral Bed contains branching colonies of the coral, *Thecosmilia martini,* forming a small patch reef (Figure 3-49). Bivalves are abundant in certain beds, although diagnostic ammonites are not common. Also present within the formation are oolitic limestones, inferring a warm, shallow sea, with sustained water movement. The clay mineralogy is montmorillonite, which implies derivation from the weathering of basic igneous rocks in the sediment source area.



Figure 3-49: Weathered surface of the Ob Breakish Coral Bed, SE of a dolerite sill on the Rubha Lusa section, west of Ob Lusa, Breakish. Coin *ca.* 20 mm across.

Browser version

The overlying Ardnish Formation (formerly Upper Broadford Beds) is 50-80 m thick and comprises similar lithologies, but without limestones, and with more abundant micaceous siltstones and shales, commonly ferruginous and commonly bioturbated (Figure 3-50; Figure 3-51; Figure 3-52). Also present are thin beds of ironstone and discrete sandstones such as the Hallaig Sandstone Member in SE Raasay. Distinctive, abundant bivalves, *Gryphaea arcuata,* the 'Devil's toenail(s)', are present, as are the ammonites, *Arnioceras* and *Coroniceras*.



Figure 3-50: Siltstone with abundant *Gryphaea (arcuata)*, Ardnish Member, Ardnish. Hammer *ca.* 30 cm long.

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Figure 3-51: Siltstone with an ammonite in cross-section, Ardnish Formation, Ardnish. Hand lens *ca*. 50 mm long.



Figure 3-52: Siltstone with cast in whorl section of the ammonite *Coroniceras* in the Ardnish Formation, Ardnish. Hammer *ca*. 30 cm long.

The Formation is well-exposed at Ardnish on the east side of Broadford Bay. Relative to the underlying Breakish Formation, the Ardnish Formation represents a more offshore, relatively deeper-water facies. The presence of an oolitic ironstone, with the mineral bertherine (chamosite), implies a greater run-off of water (with both solid and dissolved load) from the hinterland, possibly due to a wetter climate (Figure 3-53; Figure 3-54). The clay mineralogy is illite-kaolinite, which implies that the weathered material from the source area no longer involved basic igneous rocks.



Figure 3-53: Ardnish Ironstone, Rubha Ardnish, forming a small recess, with abundant fragments of reddened ironstone in the immediate area. Pole *ca.* 1 m long.



Figure 3-54: Detail of surface texture of the oolitic Ardnish Ironstone, Rubha Ardnish. Coin *ca.* 20 mm across.

Broadford

At the head of Loch Slapin, the Ardnish Formation unconformably overlies a karstic-surfaced sequence of Cambro-Ordovician Durness Group dolostones, indicating a palaeo-shoreline at this time. Here, the Breakish Formation is absent. Fossils from the semicostatum Zone are common and the basal Jurassic layer is crowded with *Gryphaea arcuata* and other bivalves attached to the underlying Cambro-Ordovician dolostones (Figure 3-55; Figure 3-56; Figure 3-57; Figure 3-58). In sea cliffs a short distance to the NW, the overall lithofacies illustrates one of the few unequivocal exposures of a Jurassic shoreline in Britain. Clefts and hollows in a palaeo-karst topography eroded in the Cambro-Ordovician dolostone are infilled with a thin sequence of sedimentary breccia, conglomerate and rhythmically bedded, silty sandstones and sandstones (Figure 3-58; Figure 3-59). These rocks comprise the Camas Malag Formation (Nicholson 1978); they are of Early Jurassic age (Amiri-Garoussi 1982) and were laid down under marine conditions (Farris *et al.* 1999).



Figure 3-55: Limestones and thin mudstones/shales of the Lusa Limestone Member at the base of the Breakish Formation, south side of the Allt nan Leac, close to the track adjacent to Loch Slapin, Strath. Pole *ca.* 1 m long.

BGS



Figure 3-56: Base of the Lower Jurassic Ardnish Formation on the east shore of Loch Slapin, north of the outflow of the Allt nan Leac. Below the angular unconformity are pale Cambro-Ordovician Durness Group dolostones forming the planar surface in the near ground. Pole *ca.*1 m long. The cliffs in the distance (to the south) are composed of Pabay Shale Formation strata.

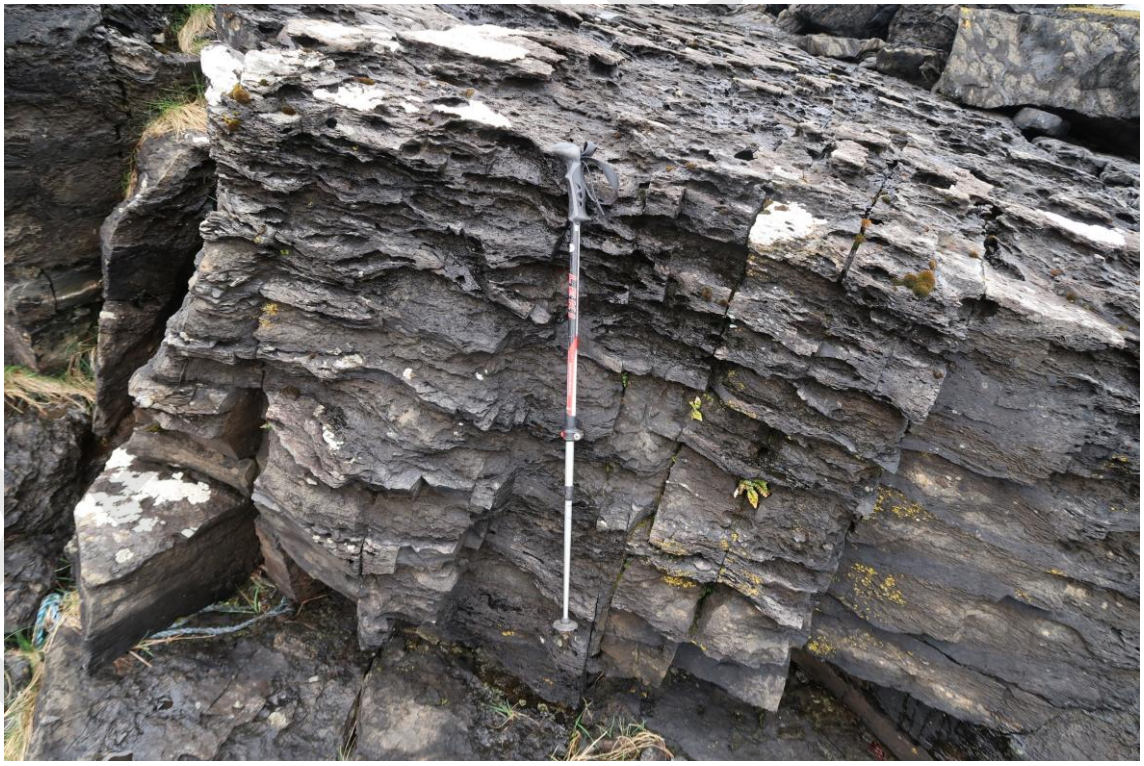


Figure 3-57: Detail of the *Gryphaea arcuata* -bearing calcareous sandstones and limestones of the Ardnish Formation, east shore of Loch Slapin. Pole *ca.* 1 m long.

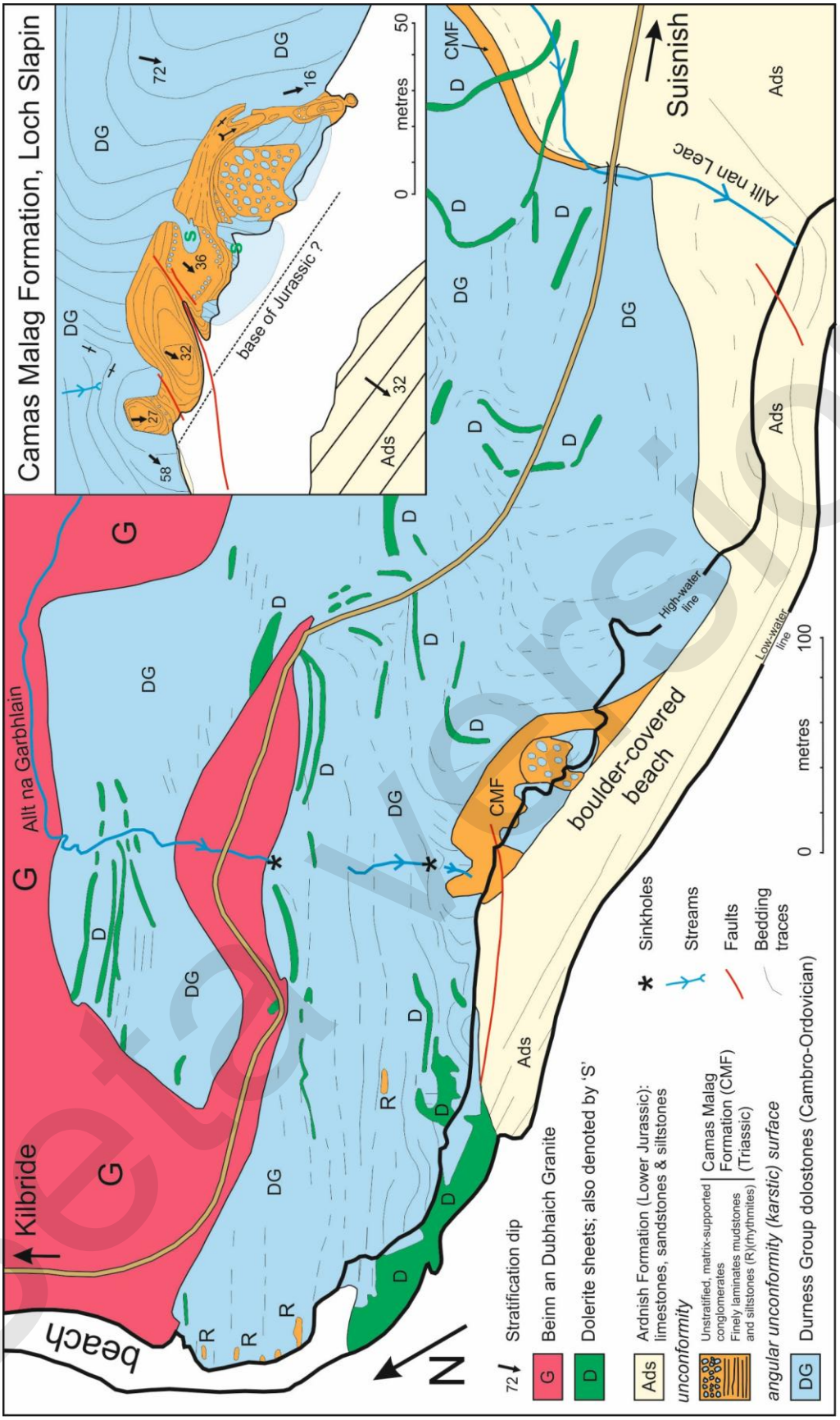


Figure 3-58: Geological map showing the location of the Camas Malag Formation, unconformably overlying deformed Cambro-Ordovician Durness Group dolostones intruded by Paleocene dolerite dykes and sheets.

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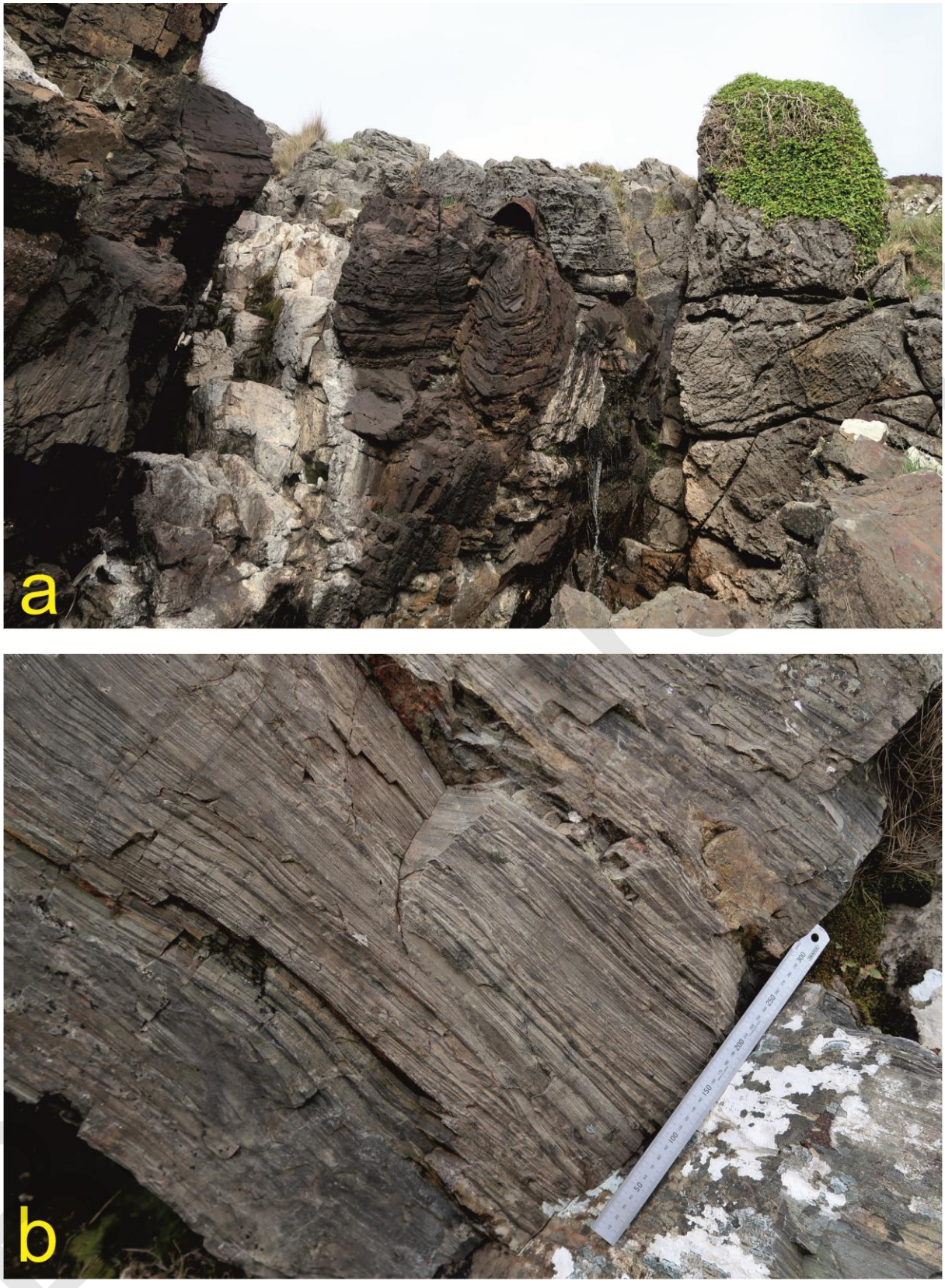


Figure 3-59: Triassic Camas Malag Formation strata, comprising inclined, thinly bedded, very fine sandstones, siltstones and mudstones on the eastern shore of Loch Slapin, south of Camas Malag, near the outflow of the Allt na Garbhain. Ruler 30 cm long.

On Strathaird, part of a tibia belonging to a carnivorous dinosaur has been found in beds of probable Sinemurian age (Benton *et al*. 1995).

The Breakish Formation is sparsely exposed on Raasay. The greatest development occurs at the east end of the bay at Hallaig, where *ca*. 35 m of interbedded limestones and mudstones are exposed. These beds contain a bivalve-dominated fauna that includes *Modiolus*, *Cardinia* and *Liostrea*. Ammonites (*Franziceras sorlei*, *liasicus* Zone) from the lowermost beds indicate that the marine transgression affected this area earlier than in the Broadford area and was therefore diachronous (Morton 1999b). Similar strata are exposed on the west side of the dismantled iron ore mine track, north of East Suisnish, south Raasay (Figure 3-60).



Figure 3-60: *Gryphaea arcuata* -bearing calcareous sandstones and limestones of the Ardnish Formation, west of the dismantled iron ore mine track, south Raasay. Pole *ca*. 1 m long.

East of Hallaig, a *ca*. 50 m thick cliff section exposes a succession of limestones and fissile mudstones in its lower part; with calcareous siltstones and micaceous sandstones (also well exposed in the waterfall at the seaward end of the Hallaig Burn) (Figure 3-61), seen at higher levels. These latter beds belong to the Hallaig Sandstone Member, which marks the top of the Ardnish Formation (Morton & Hudson 1995; Morton 1999a; compare Hesselbo *et al*. 1998). Bivalve, brachiopod and crinoid remains occur in the lower part of the member, and ammonites (*Arnioceras*, *Euagassiceras*) are present in beds *ca*. 20 m above the base, although the upper half is only sparsely fossiliferous.



Figure 3-61: Ardnish Formation strata south of the Hallaig Waterfall. View is towards the NW from the Sorley McLean Memorial cairn on the Hallaig path, SE Raasay.

3.3.2.3 Pabay Shale Formation

The overlying Toarcian Pabay Shale Formation, deposited in a deeper and more offshore marine environment, is at least 75 m thick and comprises dark grey, ammonite-bearing, predominantly bioturbated shales and siltstones, and very fine-grained sandstones, typically ferruginous and mica-rich, together with thin sandstone units (Figure 3-62; Figure 3-63; Figure 3-64). The hinterland contributed significant amounts of vegetable matter to the sediment load. Calcareous and sideritic concretions are relatively common, some containing ammonites and *Gryphaea arcuata*.

The whole formation is excellently exposed on either side of Rubha Suisnish on the shores of Loch Slapin and Loch Eishort (Figure 3-63; Figure 3-64), where a detailed succession has been established (Hesselbo *et al.* 1998), whereas on the island of Pabay (Figure 3-44), the 'type section', only the upper part of the formation is exposed, from the Suisnish Sandstone Member, upwards. The base of the formation is indicated by siltstones and shales containing ammonites (and dinoflagellate cysts) of the Obtusum and Oxynotum zones, respectively (Morton *et al.* 2024). Towards the top of the formation, mica-rich sandstones are more common and one unit, the Suisnish Sandstone Member, with a type-section near Suisnish on the north side of Loch Eishort, forms a distinct and correlatable sequence. Of remark, strata from the ammonite-defined Raricostatum Zone at Boreraig on Skye (Figure 3-63) and at Allt Fearns on Raasay (see below) (Figure 3-65; Figure 3-66; Figure 3-67; Figure 3-68) are unusually thick, which may have a regional significance (Morton *et al.* 2024).

Sinuous, lobate contacts between Paleocene basalt dykes and silty sandstones exposed in a roadstone quarry north of East Suisnish in south Raasay (and elsewhere) indicate that the sedimentary rocks were poorly consolidated and probably wet when intruded. Sandstones of the Hallaig Sandstone Member (Hesselbo *et al.* 1998) are also present at Loch Eishort, but these are now considered to belong to the Ardnish Formation (Morton 1999a).

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Figure 3-62: Pabay Shale Formation, Pabay.



Figure 3-63: Pabay Shale Formation strata on the north side of Loch Eishort, between the abandoned villages of Suisnish and Boreraig.

Publication



Figure 3-64: Pabba Shale Formation forming the cliffs on the east shore of Loch Slapin north of Rubha Suisnish. View is from Stac Suisnish, towards the NNE, with Beinn na Caillich in the distance.

On Raasay, the Pabay Shale Formation is exposed in the Allt Fearns, SW of Beinn na Leac, where it consists of dark, fissile mudstones that pass upwards into micaceous, silty rocks (Figure 3-65; Figure 3-66; Figure 3-67; Figure 3-68). Bivalves (including *Gryphaea*, *Cardinia*, and *Hippopodium ponderosa*) and a variety of ammonites (including *Echioceras*, *Crucilobiceras* and *Vininodiceras simplicostata*) occur in these beds. The involvement of these strata in a Pleistocene landslip (the Beinn na Leac Landslip) has considerably complicated the outcrop, with difficult-to-recognise faults.

The Pabay Shale Formation also crops out on SE Scalpay and on the west side of Beinn Dearg Mhòr in Strath.

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Figure 3-65: General view of the Pabay Shale Formation in the Allt Fearns, SE Raasay. View is towards the NE, with the lower slopes of Beinn na Leac in the right-hand-side background.



Figure 3-66: Discontinuous bands of pale-weathering carbonate concretions within the Pabay Shale Formation on the NW bank of the Allt Fearns, SE Raasay.



Figure 3-67: Detail of pale-weathering carbonate concretions within the Pabay Shale Formation on the NW bank of the Allt Fearns, SE Raasay.



Figure 3-68: The oyster, *Gryphaea arcuate* (the 'devil's toenails') within Pabay Shale Formation strata in the Allt Fearns, SE Raasay. Coin *ca.* 24 mm across.

3.3.2.4 Scalpay Sandstone Formation

The Pabay Shale Formation has a gradational boundary with the overlying marine Scalpay Sandstone Formation, dominated by micaceous sandstones, siltstones and calcareous sandstones. The formation takes its name from the 'type section' on the island of Scalpay, NW of Broadford Bay. On Trotternish, north Skye, it occurs in difficult-to-access sections north and south of Portree.

These tidal-influenced sandstones, with distinctive low-angle cross stratification and diagenetic sideritic concretions ('doggers'), are the product of a significant influx of sediment into the shallowing basin due to uplift of the hinterland, undergoing periods of storm conditions. The basal beds at different localities are, based upon fossil contents, of different ages, indicating a diachronous transition from the underlying Pabay Shale Formation.

The formation contains distinctive shells of the scallop *Pseudopecten aequivalvis*. Bioturbation is common. Interbedded with the sandstones are thin beds of siltstone and mudstone and, locally, at the top of the formation, an ooidal limestone (ironstone). Based on diagnostic ammonite populations, the Scalpay Sandstone Formation bridges the Pliensbachian and Toarcian stages, with *Pleuroceras* and *Dactylioceras* defining the range.

The Scalpay Sandstone Formation is prominent on the east coast of Raasay from Screapadal to Hallaig and SW to Inverarish. The formation is nearly 100 m thick east of Beinn na Leac, where micaceous siltstones and flaggy sandstones are overlain by *ca*. 30 m of massive sandstones (Figure 3-69; Figure 3-70). An abundant fauna has been obtained from black, calcareous sandstone beds with iron-rich ooids, immediately below the topmost sandstone. Bivalves are present (*Pseudopecten aequivalve*, *Gryphaea gigantea*) and several species of the ammonite *Pleuroceras*, indicating the *apyrenum* Subzone (uppermost Pliensbachian). The ooids here, and as in Jurassic ironstones elsewhere in the Inner Hebrides, are generally described as chamositic, but are more likely to be composed of the mineral berthierine, which is compositionally similar but structurally different.



Figure 3-69: Laminated Lower Jurassic Scalpay Sandstone Formation marine sandstones and siltstones, east of Beinn na Leac, SE Raasay. Pole *ca*. 1 m long.

Bookversion



Figure 3-70: Detail of laminated Lower Jurassic Scalpay Sandstone Formation marine sandstones and siltstones, east of Beinn na Leac, SE Raasay. Pole *ca*. 1 m long.

3.3.2.5 Portree Shale Formation and Raasay Ironstone Formation

The main lithostratigraphic unit within the Toarcian is the regionally-developed Portree Shale Formation, a condensed (i.e. coarse sediment starved) sequence of dark, fossiliferous, marine shales, up to 14 m thick. Above these marine strata is the Raasay Ironstone Formation, a berthierine-oolite unit up to 2.5 m thick, which was identified in 1893 and mined on Raasay between 1912 and 1919 (Draper & Draper 1990) (Figure 3-71; Figure 3-73). The ironstone contains ammonites, for example *Dactylioceras,* along with belemnites, the latter commonly with evidence of wear, possibly due to bottom currents.

The principal occurrence on Skye is in the cliffs and on the shore between Holm Island and Tianavaig Bay in Trotternish, although the beds are almost everywhere obscured by landslips. North of Portree Harbour, more than 20 m of grey, micaceous, ferruginous siltstone, ooidal ironstone and dark-weathering micaceous siltstone belong to these formations. The abundant ammonites in the uppermost of these beds indicate that they belong to the falciferum Subzone (Middle/Lower Toarcian). A thin seam of jet (a hard type of lignite, or low-grade coal) near Holm Island is at a similar stratigraphical level to the Jet Rock of Yorkshire. To the north, a borehole near to the mouth of the Bearreraig River proved *ca*. 1.6 m of sideritic chamosite oolite belonging to the Raasay Ironstone Formation, but it was not of economic grade. There are also two small exposures of the Portree Shale and Raasay Ironstone formations on the east coast of Strathaird, a short distance south of Faoilean and at Dùn Liath, on Loch Slapin.

In detail, on Raasay, the Portree Shale Formation comprises 2 to 3 m of dark, micaceous siltstone exposed in the Inverarish Burn and in nearby, abandoned opencast workings, where a thickness of 2.4 m of the overlying Raasay Ironstone Formation occurs. The base of the Raasay Ironstone Formation consists of a

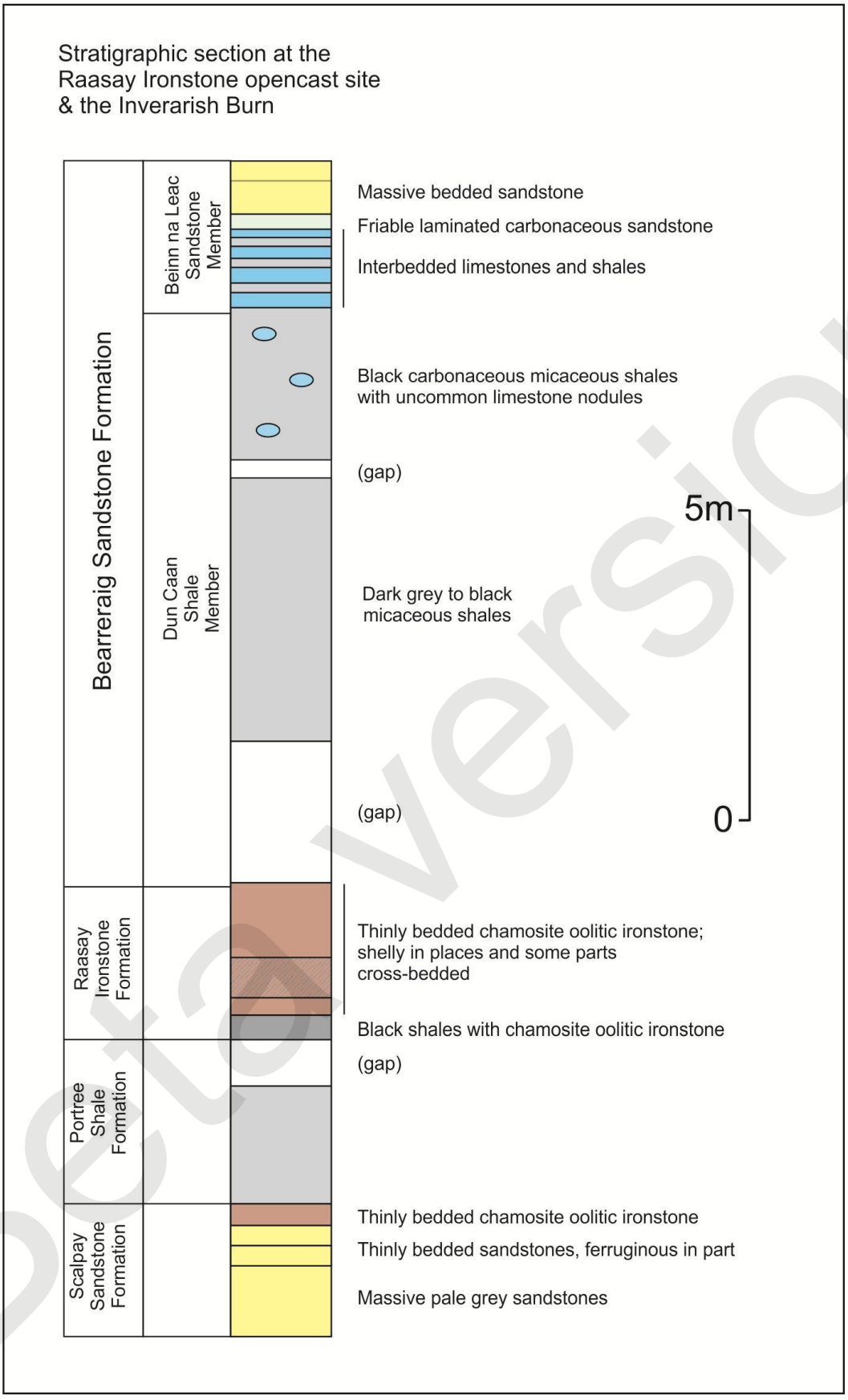
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thin chamosite ooid-bearing black fissile mudstone with abundant fossils (e.g. *Dactylioceras sp.*). A thinly bedded, ooidal chamosite ironstone, *ca.* 2 m thick, was the principal source of the iron ore. The ironstone is cross bedded in places and was deposited in shallow water. Randomly orientated belemnites are a striking feature on bedding planes exposed on the floor of the former opencast workings (Figure 3-71; Figure 3-72; Figure 3-73; Figure 3-74; Figure 3-75; Figure 3-76). Comprehensive suites of fossils have been obtained from old iron ore dumps near Suisnish Pier, including the ammonites *Dactylioceras taxophorum*, *Hildoceras laticostata*, *Harpoceras falciferum* and *Cleviceras* elegans, all from the *falciferum* Subzone (Lower Toarcian).



Figure 3-71: Belemnite- and ammonite-bearing dark grey shales forming a bedding surface of Toarcian Portree Shale Formation strata on the locally exposed floor of the abandoned opencast quarry east of the No. 1 Mine Entrance on Raasay. Ruler 30 cm long.

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Figure 3-72: Details of the stratigraphy of the Raasay Ironstone Formation, together with underlying and overlying strata.



Figure 3-73: Marine Toarcian Raasay Ironstone Formation strata forming low crags NW of the abandoned opencast quarry, east of the No. 1 Mine Entrance on Raasay. The dominant lithology is a berthierine-oolite ironstone. Pole *ca*. 1 m long.



Figure 3-74: Detail of Raasay Ironstone Formation strata at the opencast area. The pale green 'cores' are fresh material, surrounded by a boxwork of rusty-brown weathered (oxidised) material. Ruler 30cm long.

Pre-publication version



Figure 3-75: Partially flooded Mine #1 adit, with walls of Raasay Ironstone Formation.



Figure 3-76:Photomicrograph of the Raasay Ironstone Formation chamositic ooidal ironstone with echinoderm fragments in a carbonate matrix. Image *ca*. 5 mm across. View is under plane polarised light.

Thereafter, there was a major hiatus in sedimentation, before the end Toarcian (and younger) Middle Jurassic Bearreraig Sandstone Formation.

3.3.3 Arran

A remanié (older fossils found in younger rocks) mass of Lias fissile mudstone and limestone that crops out within the Paleocene Central Arran Ring-complex (Chapter 9) has yielded a large bivalve fauna belonging to the angulata Zone (Hettangian), as well as ammonite remains (*Schlotheimia*). This is the only occurrence of Jurassic rocks on Arran. When taken in conjunction with nearby remanié masses of Cretaceous rocks, it provides a strong indication that Mesozoic strata were formerly much more widely distributed over western Scotland, as they are now in Antrim, a relatively short distance to the SW (e.g. Mitchell 2004).

3.3.4 Mull

With the exception of small outcrops of limestone, calcareous mudstone and sandstone on the west coast south of Gribun, and beds of the Blue Lias (lowermost Jurassic) (Figure 3-42) and Pabay Shale formations at and near Tobermory, Jurassic rocks are restricted to the east and south of the island. The oldest Jurassic strata at Gribun contain various species of the ammonite *Psiloceras* and are underlain by bioturbated sandstones of the Penarth Group of Rhaetian age, thus making it the only Scottish outcrop that spans the Triassic-Jurassic boundary (Figure 3-42) (Morton *et al*. 2024). Lower Jurassic strata crop out in the cores of anticlines marginal to the Paleocene Mull Central Complex (Chapter 9), from Scallastle Bay almost to Loch Spelve, in many places on the SE coast from Loch Don to Loch Buie, and at Carsaig Bay in SW Mull (Figure 3-77; Figure 3-78; Figure 3-79).



Figure 3-77: Pabay Shale Formation overlain by Paleocene basaltic lavas, An Garradh cliffs, east of Loch Buie, south Mull. [Photograph courtesy of Jim Morrison]

Preview version



Figure 3-78: Scalpay Sandstone Formation forming lower third of cliff, overlain by Paleocene basaltic lavas, Sròn nam Boc cliffs, west of Carsaig Bay, Ross of Mull, SW Mull.



Figure 3-79: Columnar-jointed basaltic lavas overlying a thin sequence of Upper Cretaceous strata and pale Lower Jurassic Scalpay Sandstone Formation strata with concretions, Sròn nam Boc, west of Carsaig Bay, south coast of Brolass, SW Mull.

The beds range in age from Hettangian through to Bajocian (Mid Jurassic; *garantiana* Zone) and contain a moderately abundant marine fauna. Near Port nam Marbh, there is a fairly continuous succession from the uppermost *ca*. 30 m of the Pabay Shale Formation, represented by slightly calcareous siltstones with abundant oyster-like *Gryphaea cymbium* and the bivalve (scallop) *Pecten aequivalvis*, to the Bajocian. At

Torosay, the Pabay Shale Formation contains the Torosay Sandstone Member, which is over 20 m thick and locally cross-bedded (Hesselbo *et al*. 1998).

3.3.5 Morvern

The most complete exposures are at Loch Aline, where the Blue Lias and the Pabay Shale Formation (Figure 3-42) are each *ca*. 30 m thick The former crops out around Loch Aline, comprising alternating beds of limestone with shell-rich intervals and mudstone, and ranges from the Hettangian (Angulata Zone) to the Lower Sinemurian (Bucklandi Zone). The sequence thins eastwards towards Inninmore; north-westwards, the Lias crops out below Cretaceous rocks on the shores of Loch Teacuis but is largely absent beneath the Cretaceous and Paleocene outliers north of the loch. An early Sinemurian hiatus is recognised on Morvern, which appears to be a local phenomenon (Hesselbo *et al*. 1998) and is attributed to sediment starvation. The existence of a widespread, diachronous unconformity, supposedly early Sinemurian in the south and late Sinemurian in the north, is now discounted (compare Fyfe *et al*. 1993).

3.3.6 Ardnamurchan

Despite being much disturbed by faults and folds, and having undergone pervasive and locally severe thermal metamorphism, a relatively complete succession of Lower and Middle Jurassic rocks is preserved on the south side of the peninsula (Figure 3-80; Figure 3-81; Figure 3-82). Indurated, fossiliferous Lias mudstones, thin limestones, calcareous sandstones and thin ironstones are intruded by numerous Paleocene inclined sheets; they crop out along the southern margin of the central complex from near Port Mìn to Kilchoan, and form scattered outcrops eastwards as far as Loch Mudle. On the north coast, Lower Jurassic strata crop out at several localities for *ca*.4 km west of Fascadale Bay, and to the east more than 70 m of mudstone and limestone overlie Triassic rocks at Swordle. Ammonites from the angulata zone (Hettangian stage, with *Schlotheimia*) and bucklandi zones (Sinemurian, with *Coroniceras*), have been obtained from this area (Oates 1978).



Figure 3-80: Inclined Lower Jurassic calcareous sandstones, mudstones and limestones, Sròn Beag, SW of Kilchoan, Ardnamurchan.

Beta version



Figure 3-81: (a) Indurated Lower Jurassic calcareous sandstones, mudstones and limestones, Sròn Beag, SW of Kilchoan, Ardnamurchan, pole *ca*. 1 m long; and, (b) Fragmented belemnites within an indurated calcareous sandstone, Sròn Beag, SW of Kilchoan, Ardnamurchan, coin *ca*. 24 mm across.



Figure 3-82: Whorl section of an ammonite in a Lower Jurassic mudstone, Sròn Beag, SW of Kilchoan. Hammer *ca*. 30 cm long.

A succession of beds ranging from the Pabay Shale Formation to the Middle Jurassic Bearreraig Sandstone Formation is recognised amongst the dense cone-sheet swarms around Kilchoan and Sròn Bheag (Richey & Thomas 1930). Rocks belonging to the Portree Shale and Scalpay Sandstone formations occur among the isolated outcrops of Jurassic strata on the north coast of the peninsula.

3.3.7 Rum

Thin, fault-bound slivers of indurated to highly metamorphosed limestone, sandy limestone, sandstone, mudstone and rare ironstone are preserved within the Main Ring Fault of the Paleocene central complex (Chapter 9) on the eastern slopes of Beinn nan Stac. The limited fauna of these beds, and their lithological similarities to Lower Jurassic rocks east of Broadford, Skye, indicate that they probably correspond to the Breakish and Ardnish formations, although a thin bed of altered ironstone at Dibidil may be from near the base of the Pabay Shale Formation.

3.3.8 Shiant Isles

About 10 m of indurated fissile mudstone is preserved between Paleocene sills (Chapter 8) on the Shiant Isles. These strata have yielded ammonites of the species *Dactylioceras,* characteristic of the *falciferum* Zone. The topmost beds may be of Bajocian age.

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3.4 Middle Jurassic

3.4.1 Introduction

Following a depositional hiatus and the development of a subtle disconformity at around the Toarcian-Aalenian boundary, tectonic activity, mainly tilting of basement blocks, rejuvenated the basin margin topography and triggered a significant period of clastic sedimentation, resulting in the deposition of the shallow marine Bearreraig Sandstone Formation, the thickest onshore Jurassic clastic sedimentary sequence in the British Isles (Figure 3-42) (Morton 1965; Mellere & Steel 1996; Archer *et al.* 2019; Morton *et al.* 2024). Originally referred to as the Inferior Oolite, due to its stratigraphic position below (i.e. inferior to) the Great Oolite, a thick sequence of (marine) limestones, it is overlain by the self-evidently named Bajocian-Bathonian Great Estuarine Group, deposited in lagoons, lagoonal deltas and mudflats, which varied from freshwater through brackish to shallow marine.

Onshore exposures are largely confined to the northern part of the district, where the majority of the outcrops, including the type section/locality, occur on Skye (Figure 3-42; Figure 3-83; Figure 3-84).

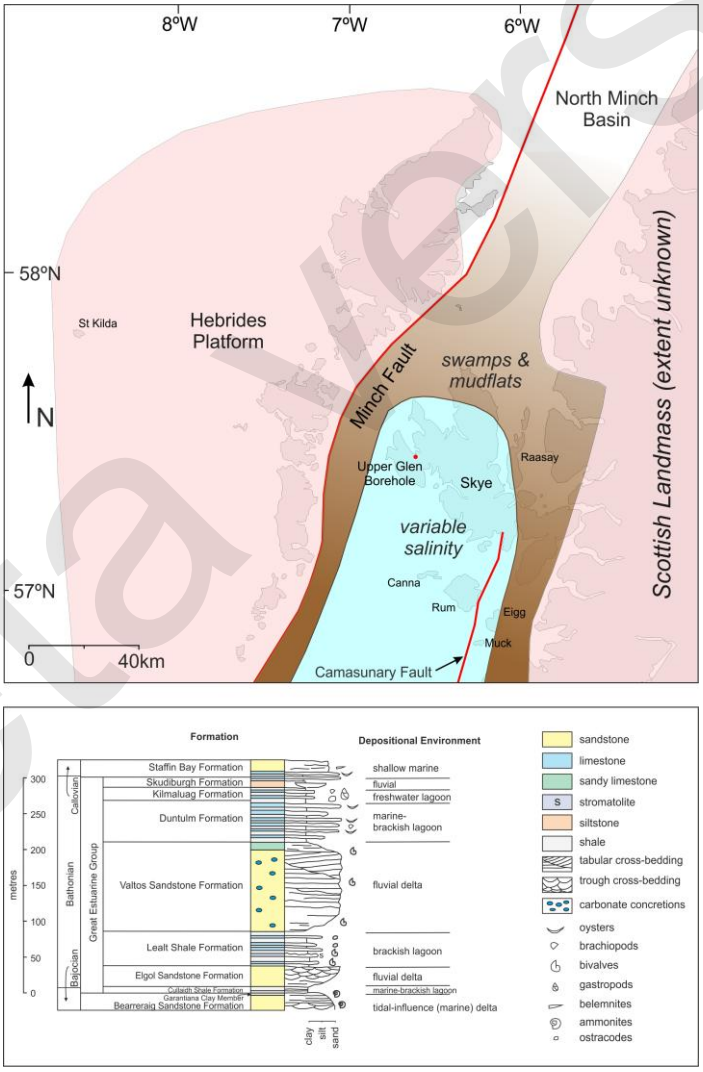


Figure 3-83: Middle Jurassic (Bathonian) palaeo-geographic map/interpretation (after Hudson & Trewin 2002) and lithostratigraphy of the Great Estuarine Group.

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Formation	Type locality [Grid Reference]	Lithology	Fauna	Depositional conditions
SKUDIBURGH	Skudiburgh, West Trotternish [NG 379 650]	mudstone, siltstone, channel-fill sandstones	generally unfossiliferous	fluvial and alluvial
KILMALUAG	Kilmaluag, NW Trotternish [NG 427 742]	calcareous mudstone, fissile limestone desiccation cracks	gastropods, conchostracans, ostracods	freshwater lagoon
DUNTULM	Duntulm Bay, NW Trotternish [NG 410 740]	fissile mudstone, limestone, nodular limestone and shell banks	oysers and other bivalves, brachiopods	marine to brackish lagoon
VALTOS SANDSTONE	Valtos, East Trotternish [NG 514 638]	sandstone with carbonate concretions	bivalves	fluvial delta
LEALT SHALE Lonfearn Member	Lonfearn, East Trotternish [NG 520 620]	interbedded fissile mudstone and limestone, desiccation cracks	ostracods, conchostracans, bivalves	brackish to marine lagoon
Kildonnan Member	Kildonnan, Eigg [NM 490 850]	algal stromatolitic limestone at top, fissile mudstone	bivalves, vertebrates	brackish to marine lagoon
ELGOL SANDSTONE	Elgol, Strathaird [NG 520 140]	sandstone	rare plant remains	fluvial delta prograding south
CULLAIDH SHALE	Port na Cullaidh, Straithaird [NG 516 137]	dark fissile mudstone, oil-shale	fish scales, gastropods	low-salinity, anoxic sediment
BEARRERAIG SANDSTONE	Bearreraig Bay, north of Portree [NG 530 515]	sandstone, cross-bedded in south. Thin mudstone at top	ammonites (common and well preserved), belemnites, bivalves, crinoids, brachiopods	shallow marine sand sheets

Figure 3-84: Subdivisions of the lower part of the Middle Jurassic sequence(s) of the Inner Hebrides, with details of type locality locations, lithologies, faunas and depositional conditions.

Excellent near-continuous sections of the Bearreraig Sandstone Formation occur at the type section on the east coast of Trotternish, Bearreraig Bay, on Strathaird in central Skye, and along the east coast of Raasay, south of Screapadal. Variations in thickness, from *ca*. 40 m to *ca*. 500 m, together with variations

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in lithology and inferred palaeo-current direction indicators such as cross-stratification, indicate significant variations in sediment transport direction and deposition. Rivers transported sediment and plant material (see below) to a coastline where tidally-influenced longshore currents distributed the dominant coarse sand, with the additional input of shell debris. At the type locality/section, three upward-coarsening cycles, from mudstones and siltstones to sandstones, infer the building out of delta lobes into the basin. These shallow marine clastic wedges exhibit apparent progradation in the *concavum* subzone of the late Aalenian, the *sauzei* zone of the early Bajocian and the *subfurcatum* zone of the latest Bajocian (Archer *et al*. 2019).

At the type section, calcareous and sideritic concretions (so-called 'doggers'), and their smaller 'variant', nodules, are common. Formation of these post-sedimentation features is attributed to deposition of material from carbonate-rich meteoric water: during diagenesis beneath the seafloor for concretions, and during early marine diagenesis with, for example, a (fossil) shell acting as a nucleus, for nodules (Wilkinson 1993; Morton *et al*. 2024) (see below).

The formation has a rich marine fauna, with ammonites, belemnites, bivalves and foraminifera, with the ammonites enabling subdivision down to subzone level (see above) and precise dating of the sequence. Plant material is relatively common, much of it permineralzed, derived from the adjacent land, indicating a coastal community dominated by conifers and an inland community dominated by ferns; some of the fern leaves are preserved as charcoal, hinting at wildfires.

The Strathaird outcrop, the Druim an Fhuarain Member, ranges in thickness from *ca*. 250 m in the north to *ca*. 500 m in the south. It has spectacular cross stratification, indicating multiple palaeo-transport directions, which vary laterally and vertically, for the dominant coarse sand. Shell debris within the sandstones is common, with fragmentation attributed to tidal action. The uppermost bed is a crinoidal limestone, which marks the termination of clastic sediment into the basin (Morton *et al*. 2024)

3.4.2 Skye and Raasay

Extensive outcrops of Middle Jurassic rocks occur on Strathaird and on Trotternish, where a complete succession from the Aalenian to the Oxfordian is preserved; a less complete sequence occurs in east Raasay.

3.4.2.1 Introduction

The Bearreraig Sandstone Formation outcrop extends for several kilometres in near-vertical cliffs in eastern Trotternish, where it comprises massive sandstones, commonly calcareous, with rich ammonite faunas at several localities (Figure 3-85; Figure 3-86; Figure 3-87; Figure 3-88; Figure 3-89; Figure 3-90; Figure 3-91; Figure 3-92; Figure 3-93; Figure 3-94; Figure 3-95; Figure 3-96; Figure 3-97). The succession, across the Aalenian–Bajocian boundary, is superbly exposed in the now-dry bed of the Bearreraig River, due to the water flow being diverted to the hydroelectric powerhouse on the south side of Bearreraig Bay. The lithology and ammonite fauna at this locality have been described in detail by Morton (e.g. in Morton & Hudson 1995), who proposed the section as the boundary stratotype for the basal boundary of the Bajocian Stage. Remains of a thyreophoran dinosaur have been recovered from the Bearreraig Sandstone Formation at Bearreraig Bay (Clark 2001). Thick sills of the Paleocene Little Minch Sill Complex intrude, disrupt and thermally alter these strata, albeit locally (Chapter 8).

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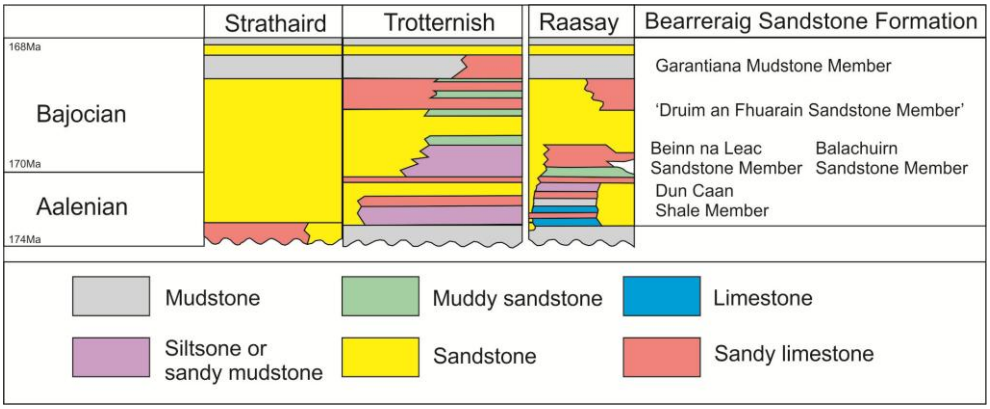


Figure 3-85: Lithostratigraphy of the Bearreraig Sandstone Formation on Skye and Raasay.



Figure 3-86: Bearreraig Sandstone Formation (?) sandstones, Udairn, SE of Portree.

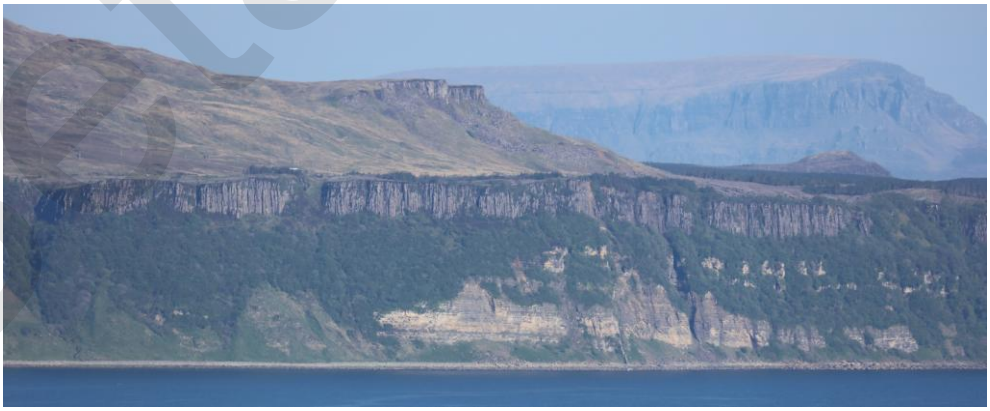


Figure 3-87: Coastal cliffs south of Bearreraig Bay, Trotternish, viewed towards the NW from Raasay. The vegetation-covered cliffs are composed of Middle Jurassic Bearreraig Sandstone Formation strata, capped by a prismatic-jointed Paleocene dolerite sill. The cliffs of The Storr form the high ground in the distance.

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Figure 3-88: Bearreraig Sandstone Formation strata south of Bearreraig Bay, Trotternish, intruded by a prismatic-jointed Paleocene sill.



Figure 3-89: Bearreraig Bay, Trotternish, location of the type section of the Bearreraig Sandstone Formation.

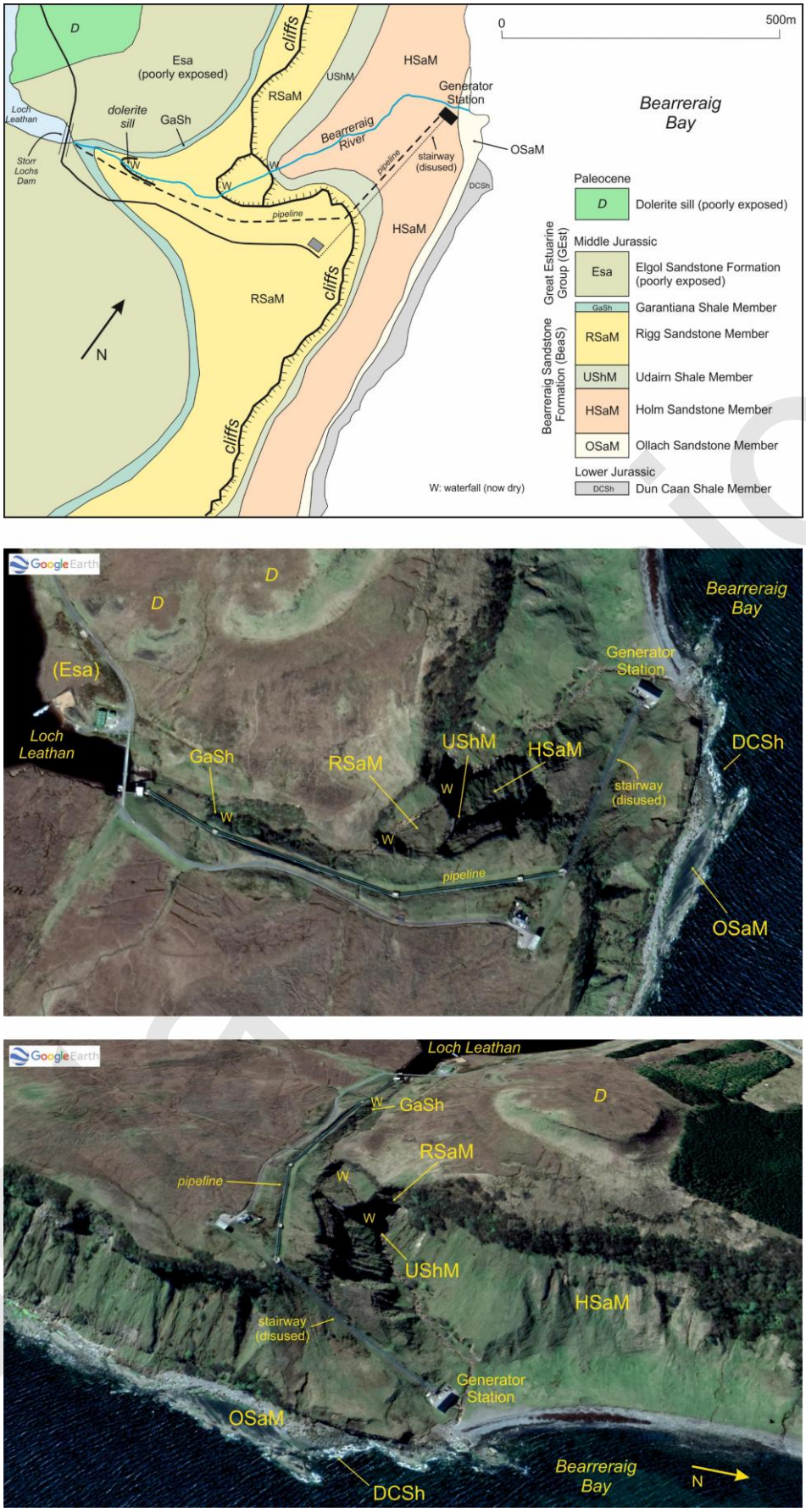


Figure 3-90: Summary geological map, key and annotated Google Earth® images of Bearreraig Bay.



Figure 3-91: Bearreraig Bay, Trotternish, viewed towards the north. The vegetation-covered cliffs are composed of Middle Jurassic Bearreraig Sandstone Formation strata, capped by a prismatic-jointed Paleocene dolerite sill.

Below the sandstones south of Bearreraig Bay, *ca*. 20 m of micaceous mudstone of the Dun Caan Shale Member (ranging from late Toarcian, but mainly Aalenian in age), rest disconformably on the Raasay Ironstone Formation (Figure 3-92).

On Raasay, the Dun Caan Shale Member crops out above the old opencast (ironstone) workings, but the thickest development (*ca*. 30 m) is at Gualann na Leac, on the NE side of Beinn na Leac.



Figure 3-92: Thin, coarsening-upwards shale-siltstone sequences within the Dun Caan Shale Member forming the rock platform on the south side of Bearreraig Bay. Pole *ca*. 1 m long.

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Figure 3-93: Calcareous concretions within the Ollach Sandstone Member, immediately above the tidal rock platform, south side of Bearreraig Bay. Pole *ca*. 1 m long.



Figure 3-94: Concretion-rich layer within the Holm Sandstone Member of the Bearreraig Sandstone Formation in the face of the main (now dry) waterfall of the Bearreraig River, Trotternish. Iain Allison for scale.



Figure 3-95: Rigg Sandstone Member forming the upper (now dry) waterfall, comprising alternating beds of shaly sandstone and calcareous sandstone.



Figure 3-96: Mould of a whorl section of an ammonite, *ca.* 30 cm in diameter, 5 m back from the lip of the upper (now dry) waterfall of the Bearreraig River, within the Rigg Sandstone Member. Hammer *ca.* 30 cm long.



Figure 3-97: Coastal exposures of Bearreraig Sandstone Formation strata intruded by a prismatic-jointed Paleocene sill, with Paleocene lavas forming The Storr and associated landslipped masses of lava, including The Old Man of Storr, in the distance.

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Similarly thick sequences crop out in east Raasay, at Druim an Aonaich and at Beinn na Leac in south Raasay (Figure 3-98; Figure 3-99; Figure 3-100; Figure 3-101; Figure 3-102).



Figure 3-98: Crags of the Druim an Fhuarain Sandstone Member of the Bearreraig Sandstone Formation, inland from the east coast of Raasay at Creag na Bruaich, south of Eaglais Breige. These Middle Jurassic tidally influenced shallow marine sandstones form a spectacular exposure, with at least 100 m of near-vertical relief. Note incipient landslip failure at north (right-hand) end of the cliff.



Figure 3-99: Well-sorted, carbonate-cemented, medium- to coarse-grained, cross-stratified sandstones, part of the background tidally influenced, dune facies sedimentation. Person for scale. [Photograph courtesy of Stuart Archer]

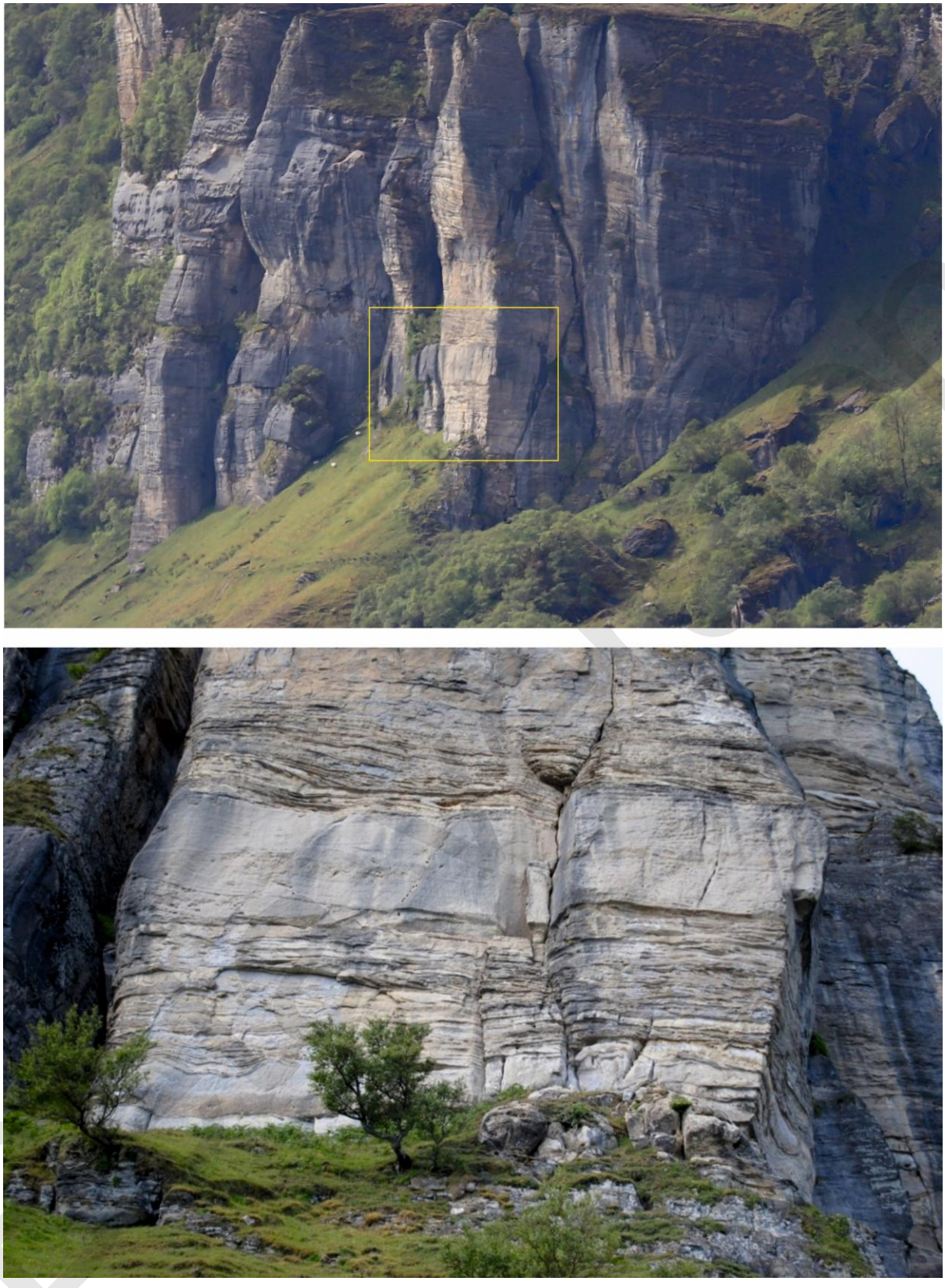


Figure 3-100: Thick, relatively homogeneous, channel-fill sandstone(s), interbedded with 'background' dune-bedded sandstones. Thickness of interval in image is *ca*. 25 m. View is towards the west. [Photographs courtesy of Stuart Archer]



Figure 3-101: East facing inland cliffs of the shallow marine Middle Jurassic Druim an Fhuarain Sandstone Member, Bearreraig Sandstone Formation, between the Hallaig track and the summit of Beinn na Leac.



Figure 3-102: Detail of the east-facing inland cliffs of the parallel-bedded, shallow marine Middle Jurassic Druim an Fhuarain Sandstone Member, Bearreraig Sandstone Formation, between the Hallaig track and the summit of Beinn na Leac. Note the distinctive style of weathering of parts of the section due to its carbonate content.

Farther south, on Skye, the Druim na Fhuarain Sandstone Member of the Bearreraig Sandstone Formation forms a broad bench on the west side and a cliff on the east side of the southern portion of Strathaird. These sandstones are predominantly (and spectacularly) cross-bedded and contain rare ammonites (Figure 3-103; Figure 3-104; Figure 3-105; Figure 3-106). The cross stratification orientation varies both laterally and vertically (i.e. temporally), indicating multiple transport/deposition directions, which can be attributed to the complexity of tidal flow action distributing the sediment. In keeping with this vigorous depositional environment, a large proportion of the fossils are preserved only as shell fragments. In southern Strathaird, up to 470 m of sandstone is present, capped by *ca*. 12 m of pyritiferous fissile mudstone, the Garantiana Shale Member. The abrupt change from sandstone to mudstone at the base of the Garantiana Shale Member marks the onset of deeper water conditions and corresponds to a widely recognised transgression elsewhere (Figure 3-107). The sandstones thin northwards and cross stratification appears at progressively higher horizons, such that, on Raasay, the cross-stratified sandstones do not occur until well above the Aalenian–Bajocian boundary (see above). There, the sedimentary structures indicate an NNE-directed transport direction.



Figure 3-103: Coastal cliff exposures of the Druim an Fhuarain Member of the Bearreraig Sandstone Formation on the east side of Strathaird.



Figure 3-104: Large-scale cross-stratification of the Druim an Fhuarain Member of the Bearreraig Sandstone Formation, south of Elgol, west coast of Strathaird. View towards the north. Pole *ca*. 1 m long.

Pre-version



Figure 3-105: Large-scale cross-stratification of the Druim an Fhuarain Member of the Bearreraig Sandstone Formation, south of Elgol, west coast of Strathaird. View towards the SE.



Figure 3-106: Large-scale cross-stratification of the Druim an Fhuarain Member of the Bearreraig Sandstone Formation, south of Elgol, west coast of Strathaird. View towards the SE.



Figure 3-107: Thermally altered (hornfelsed) thinly laminated, pyritiferous shales and siltstones of the Garantiana Clay/Shale Member, above the Druim an Fhuarain Member sandstones and below a Palaeocene dolerite sill, south of Elgol, west coast of Strathaird. Ruler 30 cm long.

3.4.2.2 Great Estuarine Group

The Great Estuarine Group was first recognised by Judd (1878), although originally defined as the Great Estuarine Series, and, as its name implies, was deposited in a coastal setting, varying between a deltaic environment and shallow marine conditions, frequently with the development of brackish lagoon(s) (Figure 3-108). The outcrop on the west coast of Strathaird is one of the most complete sequences, although certain of the formation names are appropriately taken from elsewhere in the Inner Hebrides (Figure 3-109) (see below).

The formation maintains its thickness and duration throughout the basin and the seven recognised members (see below) are readily recognised from the disparate outcrops throughout the Inner Hebrides. A good example of this is a cyanobacterial stromatolite, a distinctive unit within the Kildonnan Member of the Lealt Shale Formation.

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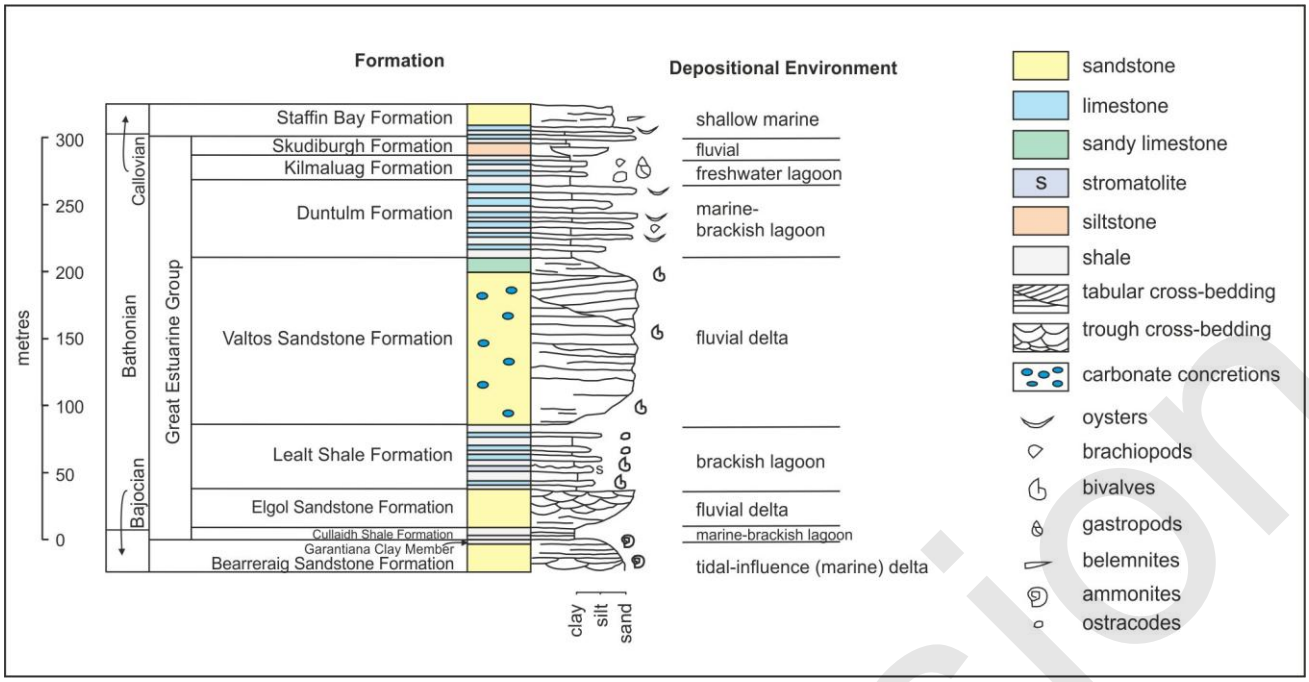


Figure 3-108: Lithostratigraphy of the Great Estuarine Group.

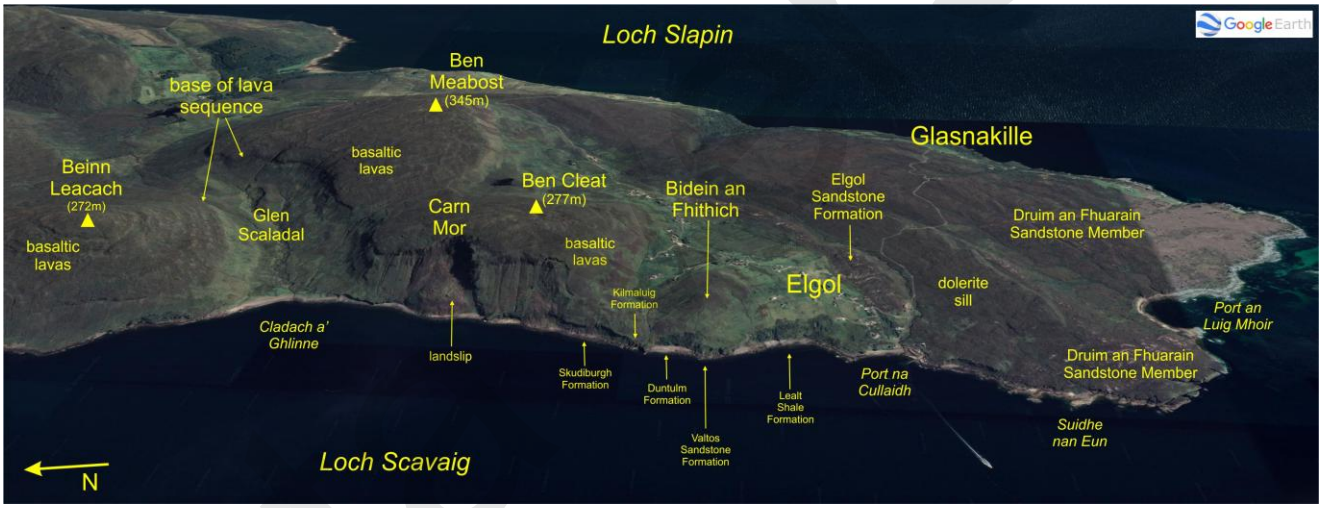


Figure 3-109: Annotated oblique Google Earth© image of the west coast of Strathaird, indicating the locations of exposure of the Druim an Fhuarain Sandstone Member of the Bearreraig Sandstone Formation, and members of the Great Estuarine Group.

The lowest unit of the Great Estuarine Group is the Cullaidh Shale Formation, which consists of dark, bituminous, fissile mudstones and dark sandstones; it varies in thickness from *ca.* 12 m in the south of Skye to *ca.* 2 m in the north. It is well exposed at Elgol on Strathaird, although this may vary due to the amount of cover caused by the constantly shifting beach sediment (Figure 3-110). The formation overlies, with a gradational boundary, the Garantiana Shale Member (see above), and may cross the Bajocian–Bathonian boundary. In the section on Strathaird, this junction is obliterated by a thick Paleocene dolerite sill. This petroliferous shale, with a high TOC (total organic content) was originally described as an oil shale and contains non-marine mytilid bivalves, conchostracans (small bivalved brachiopods), freshwater ostracods and fish scales.

Pre-release version

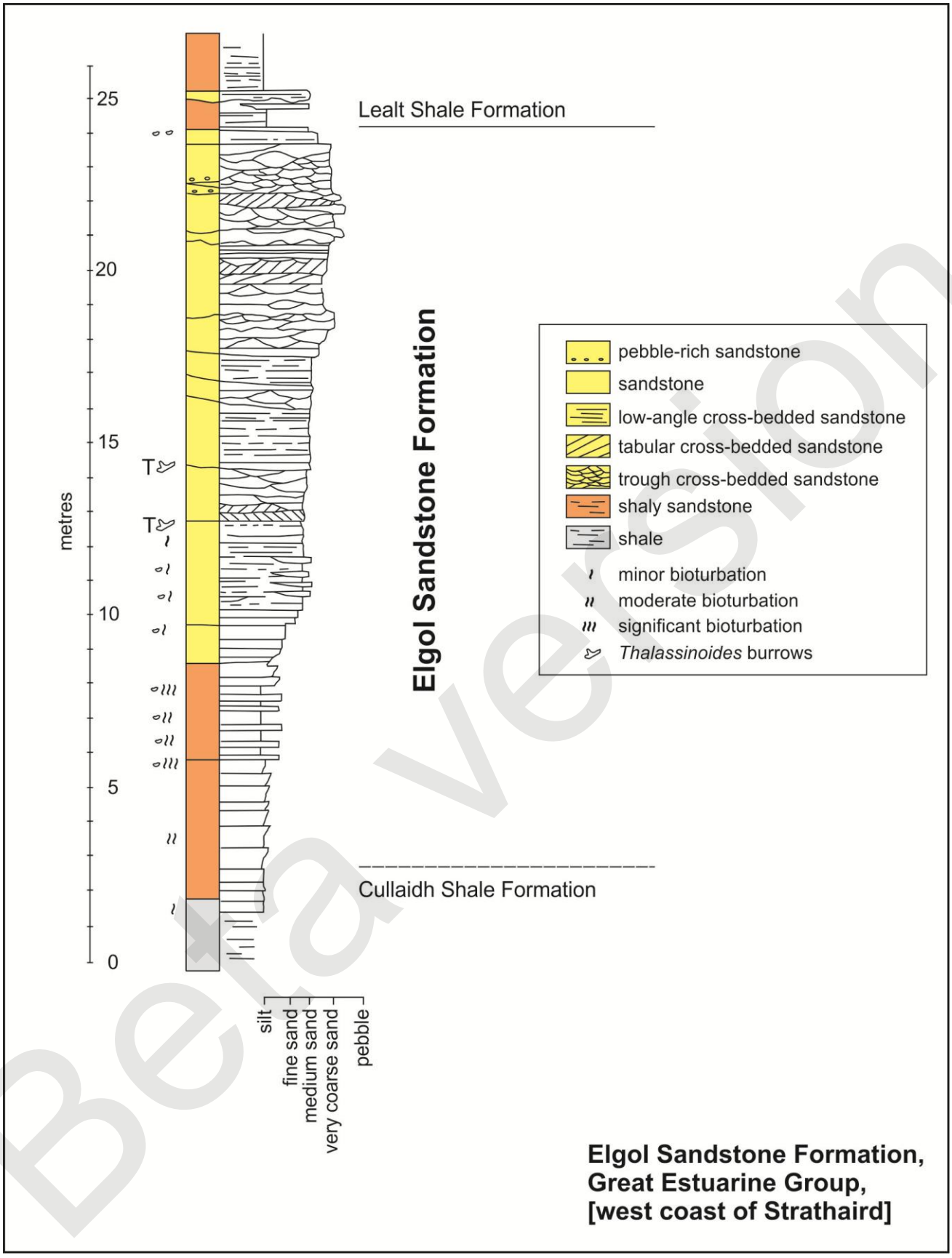
The Cullaidh Shale Formation is overlain, with a gradational boundary, by the *ca*. 30 m thick Elgol Sandstone Formation, which comprises a white, cross stratified, non-calcareous, siliciclastic sandstone, interpreted to have formed as part of a lobate delta (Figure 3-111; Figure 3-112; Figure 3-113; Figure 3-114; Figure 3-115; Figure 3-116) (Morton & Hudson 1995). At the type locality, it consists of a classic coarsening-upwards deltaic cycle (Harris 1989) and forms a prominent cliff with spectacular honeycomb weathering. The lowest part of the sandstone sequence is heavily bioturbated (Figure 3-113). (see below). The formation differs from others in the Great Estuarine Group by its distinctive and identification informative lack of calcareous concretions.

This honeycomb texture of the sandstone in the Elgol section is primarily the result of *present-day* salt induced weathering, a process driven by the crystallization of salts within the porous sandstone. In coastal environments, sea spray and saline moisture penetrate the rock's surface and, as the water evaporates, salt crystals grow and exert pressure on the mineral grains, gradually breaking them apart. Over time, this leads to the formation of small pits that expand and merge into the distinctive honeycomb or tafoni patterns. Variations in the rock's porosity and cementation make certain areas more vulnerable to erosion, enhancing the uneven, patterned appearance. The combination of salt action, wind, and wetting-drying cycles in the marine environment makes this an ongoing and dynamic process.



Figure 3-110: Fissile, organic-rich, dark grey shales of the Cullaidh Shale Formation, exposed on the beach at Elgol, Strathaird, on the foreshore immediately west of the school building and north of where the Allt Port na Cullaidh flows into Loch Scavaig. Exposure is temporal, at times good, but can also be poor. Pole *ca*. 1 m long.

Preview version



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Figure 3-111: Lithology log for the Elgol Sandstone Formation, Elgol, Strathaird (based on Morton & Hudson 1995).

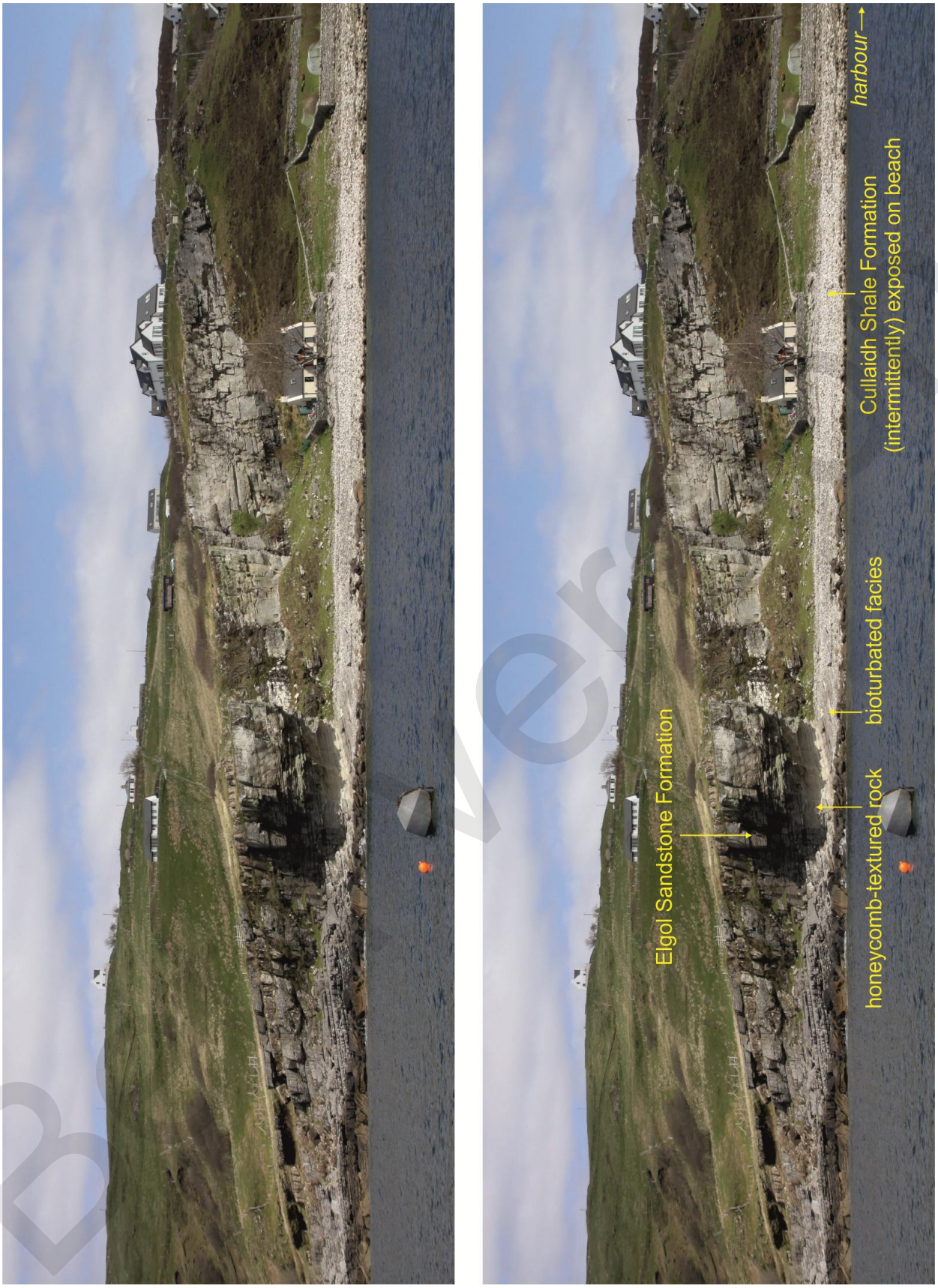


Figure 3-112: Gently inclined pale sandstones of the Elgol Sandstone Formation exposed on the west side of Strathaird at Elgol, *ca*. 150 m north of where the Allt Port na Cullaidh flows into Loch Scavaig. View towards the east.



Figure 3-113: Bioturbated sandstone in the lower part of the Elgol Sandstone Formation, Port na Cullaidh, Elgol. Ruler 30 cm long.



Figure 3-114: Gently inclined pale sandstones of the Elgol Sandstone Formation exposed on the west side of Strathaird at Elgol, *ca.* 150 m north of where the Allt Port na Cullaidh flows into Loch Scavaig. View towards the east.



Figure 3-115: Honeycomb-textured interval in the Elgol Sandstone Formation, Port na Cullaidh, Elgol, Strathaird.



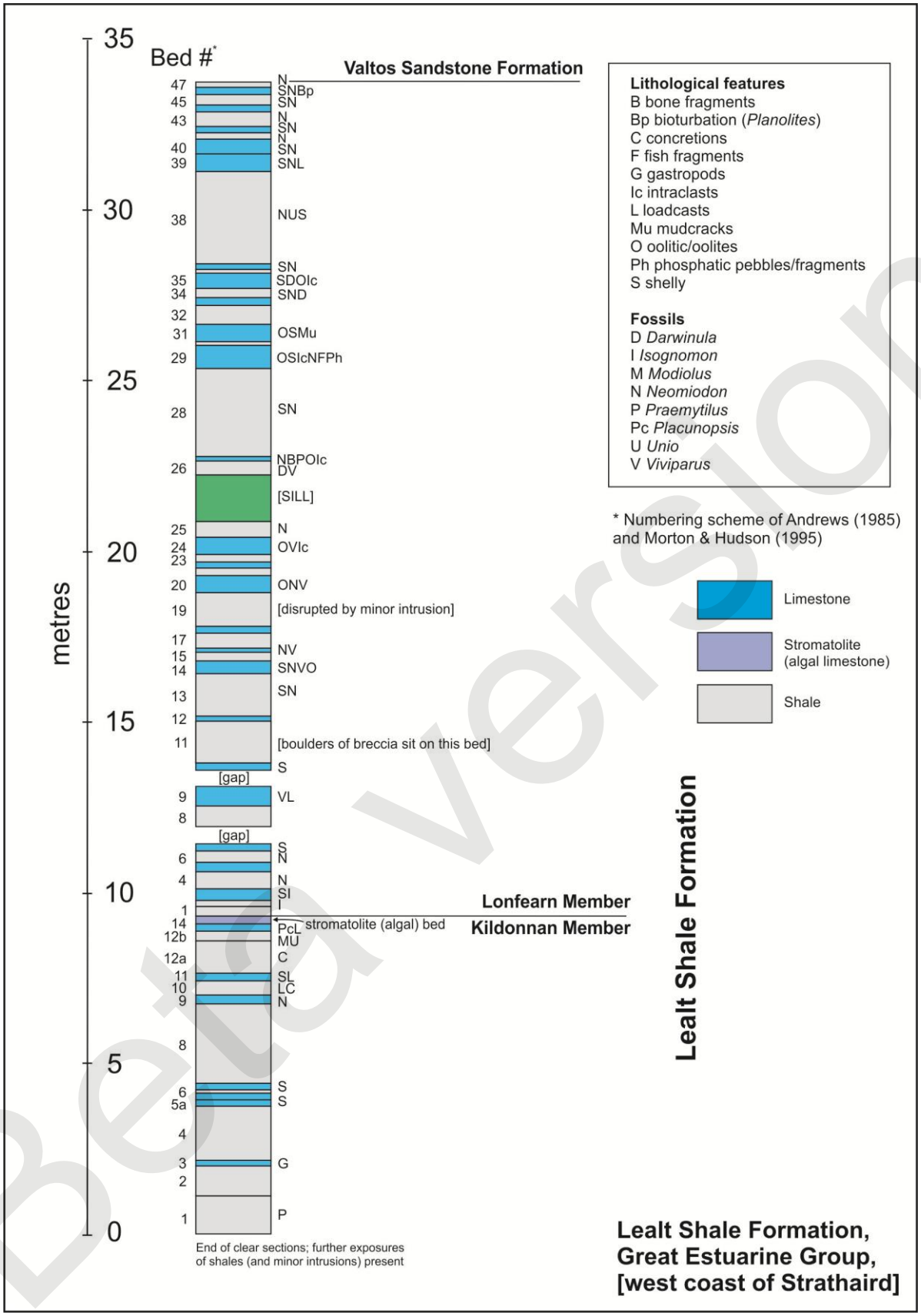
Figure 3-116: Detail of honeycomb-textured interval in the Elgol Sandstone Formation, Port na Cullaidh, Elgol, Strathaird. Pole *ca*. 1 m long.

The boundary between the Elgol Sandstone Formation and the overlying fossil-rich Lealt Shale Formation is sharp, marking an abrupt change in depositional environment The latter is divided into two members. The formation is well exposed in the coast section north of Elgol, Strathaird. Re-alignment of the road north of Portree has somewhat obscured the original type section at Lealt, but sections are available at the base of the steep cliff between Inver Tote and Lonfearn.

The lower unit is the Kildonnan Member and comprises, predominantly, shales and siltstones, at the top of which is a (basin-wide) thin, shallow-water, cyanobacterial stromatolite (Figure 3-117; Figure 3-118; Figure 3-119; Figure 3-120) (exposed on Eigg, the type section/locality, see below, and elsewhere throughout the district). The overall fossil content of the member, including shells of the mussel *Praemytilus,* are indicative of a lagoon with freshwater input (Morton *et al*. 2024).

The overlying Lonfern Member comprises shales and thin shelly, less commonly oolitic, limestones, also indicating low energy conditions and a slow rate of sedimentation. Ostracods and bivalves in the lowest part of the member indicate a brackish to marine environment, whereas higher up the sequence, conchostracans, ostracods and the cast of a bipedal dinosaur footprint indicate shallow carbonate mudflats (Andrews & Hudson 1984). The mudflat was most likely emergent and, to some extent, consolidated/lithified when the footprint was made, corroborated by desiccation cracks in other stratigraphically close beds.

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Figure 3-117: Lithology log for the Lealt Formation, Elgol, Strathaird (based on Morton & Hudson 1995).



Figure 3-118: Stromatolite in the KIldonnan Member of the Lealt Shale Formation, in the bay north of Port na Cullaidh at Elgol, Strathaird. Pole *ca*. 1 m long; coin *ca*. 24 mm across.



Figure 3-119: Type section of the Lealt Shale Formation, Lealt River, Inver Tote, Trotternish.



Figure 3-120: Horizontally bedded Lealt Shale Formation, between two sills of the Little Minch Sill-complex, Lealt River, Inver Tote, Trotternish.

The boundary between the Lealt Shale Formation and the overlying Valtos Sandstone Formation is gradational, with the incoming of silts and sands; the non-marine bivalve *Neomiodon* provides an

environmental indicator. The formation is recognised by distinctive, basin-wide exposures of pale-yellow sandstones that commonly contain abundant large, near-spherical, carbonate concretions (so-called 'doggers', see *Berreraig Sandstone Formation,* above), together with shell-rich limestones (Figure 3-121; Figure 3-122; Figure 3-123; Figure 3-124; Figure 3-125). Wilkinson (1992) concluded that these concretions were formed at depths of several hundred metres at temperatures of 30-40° C, when meteoric pore waters dissolved carbonate from shells, subsequently involved in the growth of the concretions. The concretions started to grow *ca*. 15 m.y. after burial of the host sediments (i.e. post-compaction) and the larger, metre-sized examples may have taken several million years to form. Paxton *et al*. (2023) present a more nuanced interpretation whereby at least part of their development involved Paleocene fluids, possibly of hydrothermal origin, in the temperature range 50-100°C; formation and final compaction took *ca*. 2.6 m.y.

The formation has been interpreted as a system of delta lobes, indicated by lateral variations in thickness and sand content, which built out into the lagoons in which the Lealt Shale Formation had previously been deposited (Hudson & Harris 1979; Harris 1992; Morton *et al*. 2024). Variations in mineral content indicate a lithological complex hinterland source (Morton *et al*. 2024).

At Valtos on Trotternish, the type section is *ca*. 120 m thick, with two cross-bedded, upward-coarsening sandstones of similar thickness, separated by *ca*. 27 m of fine-grained sandstones, silty mudstones and limestones containing *Neomiodon* shells. There is evidence of cyclic sedimentation; in places five cycles of mudstone and limestone passing up into sandstone with concretions have been recognised.

The Valtos Sandstone Formation near to the type section has yielded diverse bone casts/moulds and fossil footprints (Figure 3-123), including a bone from a sauropod dinosaur (Clark *et al*. 1995). On Strathaird, the Valtos Sandstone Formation lacks the distinctive concretions and is, instead, dominated by sandy (clastic) limestones (Figure 3-126). On Raasay, exposures of concretionary Valtos Sandstone Formation strata occur between Dùn Caan and the Screapadal Fault. Despite induration and alteration by the adjacent Paleocene granite, concretions are still visible in the Valtos Sandstone Formation on the eastern slopes of Glas-Bheinn Bheag in Strath, Skye, where it dips steeply eastwards. The Valtos Sandstone Formation is also present in NW Skye, at Loch Bay and Waterstein.



Figure 3-121: Valtos Sandstone Formation sandstones forming the cliff south of the Kilt Rock on the east coast of Trotternish. The dark, columnar-jointed units are sills of the Little Minch Sill-complex. View is towards the south.

Beta version



Figure 3-122: Pale sandstones with carbonate concretions of the Valtos Sandstone Formation, Dùn Dearg, Valtos, Trotternish. Hammer *ca*. 50 cm long.



Figure 3-123: Cast of a tridactyl dinosaur footprint. Loose block, Valtos, Trotternish. Ruler scale.



Figure 3-124: Shallow (nearshore) marine, *Neomiodon*-rich limestone ('shell bank') in the Valtos Sandstone Formation, north of Rubha nam Brathairean, Trotternish. Coin *ca*. 24 mm across.



Figure 3-125: Cavity lined with calcite crystals in a Valtos Sandstone Formation limestone, north of Rubha nam Brathairean, Trotternish. Coin *ca*. 24 mm across.



Figure 3-126: Sandy limestones of the Valtos Sandstone Formation, west coast of Strathaird

The boundary between the Valtos Sandstone Formation and the overlying Duntulm Formation is marked by a change in the bivalve types, with non-marine *Neomiodon* in the former and *Placunopsis* and *Modiolus* in the latter, together with the incoming of the oyster *Praeexogyra hebridica* which can dominate some shell banks.

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The base of the overlying Duntulm Formation is marked everywhere by the presence of limestone beds crowded with the remains of the oyster *Praeexogyra hebridica*. Fossil shell banks, up to 2 m thick, developed in marine to brackish water lagoons (Figure 3-127) (Andrews & Walton 1990). At Duntulm, *ca*. 55 m of strata consists of interbedded mudstones and limestones with a marine to brackish water fauna. Several of the limestones contain nodular cyanobacterial (algal) masses (Hudson & Trewin 2002). Interbedded sandstones with plant debris were deposited by freshwater floods or storms.



Figure 3-127: Fossil shell bank dominated by the oyster *Praeexogyra hebridica*, Duntulm Formation, Cairidh Ghlumaig, Duntulm, Trotternish. Ruler scale.

Dinosaur tracks occur in the type-locality sequence of the Duntulm Formation on the coast at the northern end of Lùb an Sgòir at Cairidh Ghlumaig, Duntulm, on the west side of Trotternish (Figure 3-128), and at Staffin Slipway on the east side of Trotternish (Figure 3-129; Figure 3-130) (Clark *et al*. 2004; Brusatte *et al*. 2015). Their presence provides clear evidence that parts of the Duntulm Formation sequence(s) were deposited in a shallow, near-shore to emergent environment.

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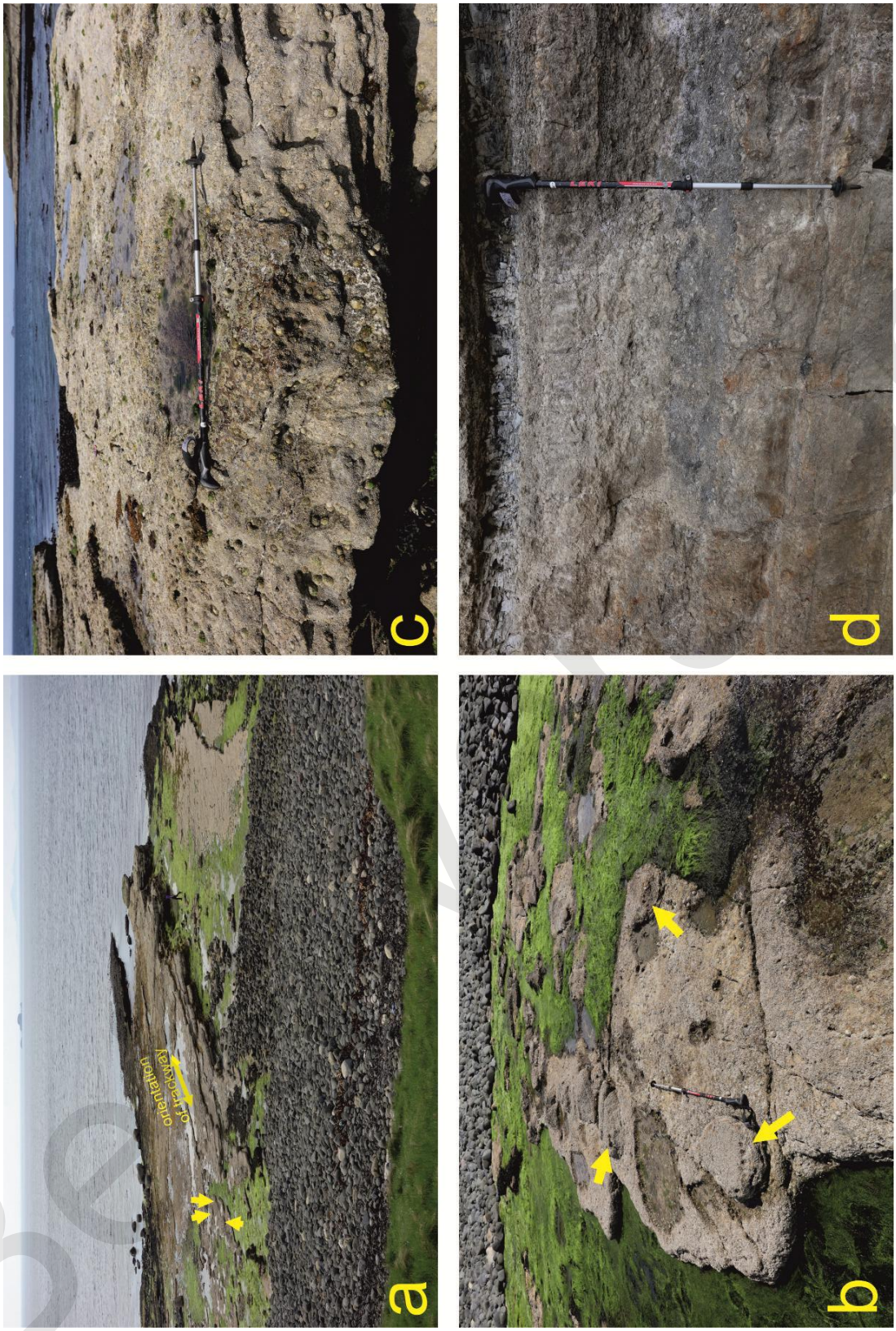


Figure 3-128: (a) Duntulm Formation strata at the type-section, Cairidh Ghlumaig, Duntulm, at the northern end of Trotternish, with indication of location and orientation of sauropod pes(= foot) prints (= ichnites); (b) bedding surface with main trackway of fossil footprints (ichnites) in hypo-relief indicated by arrows, pole *ca*. 1 m long; (c) section through bed with detail of sauropod convex hypo-relief pes (i.e. foot) print, pole *ca*. 1am long; and, (d) shaly mudstones and siltstones with abundant oyster (*Praeexogyra hebridica*) shells, pole *ca*. 1 m long.

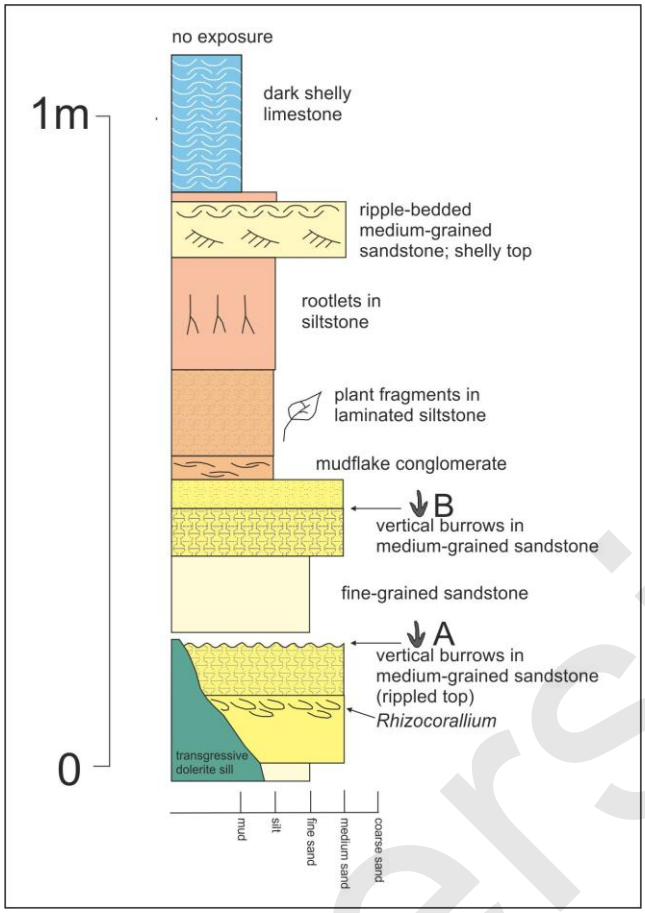


Figure 3-129: Summary lithological log for the Duntulm Formation strata on the east coast of Trotternish, NW of Staffin Slipway, indicating stratigraphic position of tridactyl dinosaur footprints.



Figure 3-130: Mould of a footprint of a tridactyl (three-toed) bipedal (two-legged) dinosaur (right of pole), possibly an herbivorous variety, in the Duntulm Formation, Staffin Slipway, Trotternish. Part of a trackway on a sandstone surface. Pole *ca*. 1 m long.

Towards the top of the section there are indications of terrigenous influence and freshwater incursions as the beds are sandier and contain the bivalves *Unio* and *Neomiodon*. There are a few poor exposures of the Duntulm Formation on Raasay.

Beta version

The formation is also present further south, on the west coast of Strathaird, where there is no indication of a freshwater influence or that land was nearby (Figure 3-131; Figure 3-132; Figure 3-133). There are minor fossiliferous outcrops at Loch Mòr, Waternish and Waterstein Head, Duirinish.

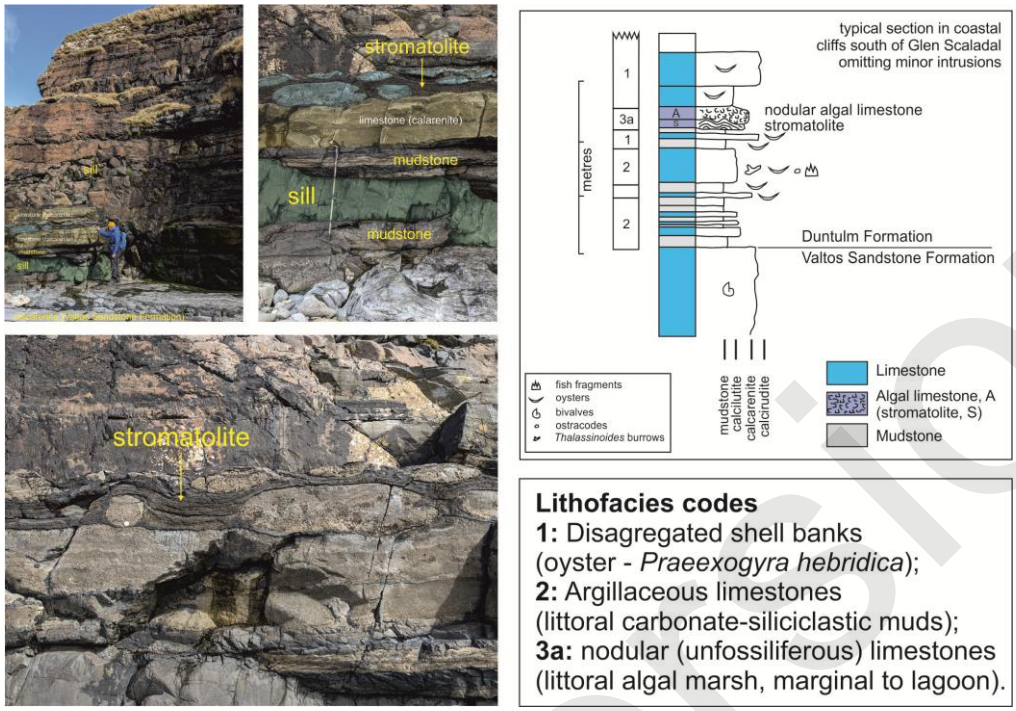


Figure 3-131: Field views and lithological log of the basal section of the Duntulm Formation, south of Cladach a' Ghlinne, west coast of Strathaird, including an algal stromatolite *ca*. 2 m above the base of the formation.



Figure 3-132: *Praeexogyra hebridica* -bearing limestone (south Scaladal cliff, fallen block). Coin *ca*. 24 mm across.

Borehole version



Figure 3-133: Detail of *Praeexogyra hebridica* -bearing limestone (south Scaladal cliff, fallen block). Coin *ca.* 24 mm across.

The overlying Kilmaluag Formation consists of calcareous mudstones with alternations of indurated layers which may be nodular; some are also dolomitic. Thin sandstones are present in the Trotternish successions, where Andrews (1985) recognised a 'clastic facies', although these are not found in the southern localities on Skye, nor on Eigg and Muck, which instead have an 'argillaceous limestone facies'

(see below). The freshwater gastropod *Viviparus* and the freshwater bivalve *Unio* are present, but they are not as abundant as non-marine ostracods (e.g. *Theriosynoecum*) which gave the formation its former name, the Ostracod Limestones.

The formation also occurs at Waternish and is well exposed on Strathaird but is not present on Raasay.

These beds are interpreted as having been deposited in short-lived lagoons, with the fossil faunas indicating deposition in low salinity environments. Theropod and sauropod trackways have been recorded from the west coast of Trotternish at Prince Charles's Point, Totscore (Figure 3-134) (Blakesley *et al.* 2025).

In the Strathaird section, the lower part of the Kilmaluag Formation comprises dominant shales, but with an upward increasing proportion of limestones, many with desiccation cracks (Figure 3-135). The upper part of the sequence contains freshwater hard (blue-grey) argillaceous limestones with interbedded siltstones and shales with calcareous nodules. This is the sequence which contains mammal remains (Wadman & Savage 1972), subsequently named the *Vertibrate Beds* by Andrews (1985). Benson *et al.* (2023) report an abundance of skeletal material from the Strathaird site, including fragments of pterosaurs, stem-salamanders and squamates.



Figure 3-134: Mould of a footprint of a theropod dinosaur in rippled Kilmaluag Formation sandstones at Prince Charles's Point, Totscore, Trotternish. Pole *ca.* 1 m long.

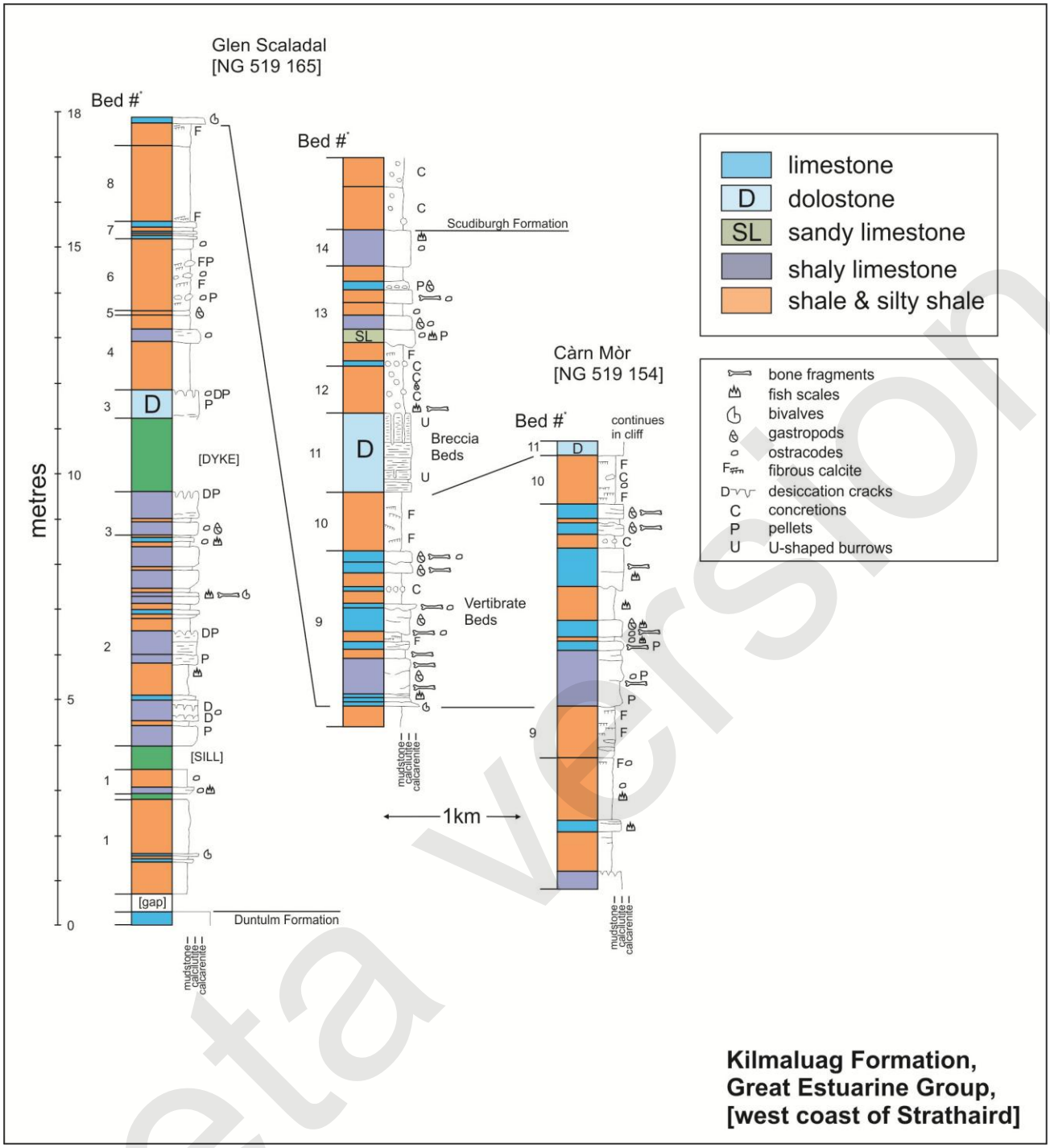


Figure 3-135: Lithology log of the Kilmaluag Formation, west coast of Strathaird (based on Morton & Hudson 1975).

The overlying Skudiburgh Formation consists of *ca*. 15 m of red and grey-green mottled silty mudstones, together with dark claystones, sandstones and lenses of silty sandstone (Figure 3-136). From its variegated colours it was formerly known as the Mottled Clay. At the type locality, the claystone and siltstone sequence is *ca*. 3.5 m thick and contains channel sands and small calcareous concretions, possibly caliche. The Skudiburgh Formation also marks the top of the Great Estuarine Group in the Strathaird succession. The formation is of alluvial origin; floodplain, channel and overbank deposits are present, which formed in a coastal plain, terrestrial environment during a late Bathonian regression (Andrews 1985).

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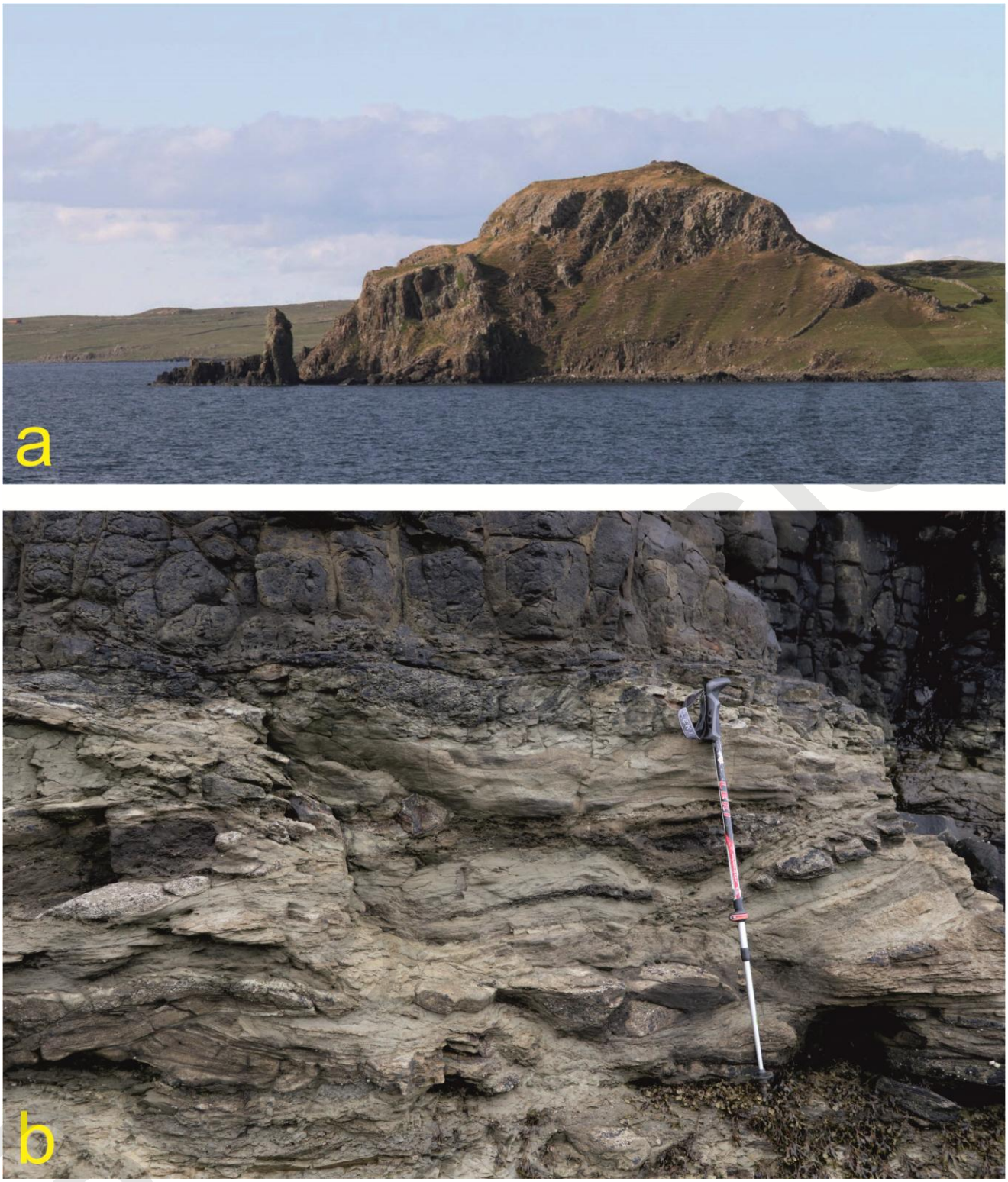


Figure 3-136: (a) View of Stack of Skudiburgh and Dùn Skudiburgh, Trotternish, composed of Skudiburgh Formation strata intruded by a (now capping) sill of the Paleocene Little Minch Sill Complex; and, (b) detail of pale, laminated, channelised Skudiburgh Formation strata, intruded by thin stringers of (the overlying) sill material, pole *ca*. 1 m long.

3.4.3 Eigg and Muck

The Middle Jurassic successions of Eigg and Muck have been described in some detail by Hudson (in Emeleus 1997). The *ca*. 150 m thick succession on Eigg is the most complete and comprises strata that range from the top of the Bearerraig Sandstone Formation up to the Kilmaluag Formation. The principal outcrops are in cliffs on the west coast, from the Bay of Laig to near Eilean Thuilm in the north of the island; discontinuous exposures also occur on the foreshore and at the base of the Paleocene lavas on the east coast. On Muck, the top of the Valtos Sandstone Formation, a full succession of highly fossiliferous Duntulm Formation strata, and the lower part of the Kilmaluag Formation are all well exposed on the foreshore at Camas Mòr.

The Bearreraig Sandstone Formation is limited to small exposures of calcareous sandstone with bivalve remains, at and below the high-water mark in NE Eigg. The overlying Lealt Shale Formation is well exposed on the north shore, although there the outcrops are greatly complicated by dolerite sheets and in places are obscured by landslips. Both the Kildonnan and the Lonfern members are present, separated by the distinctive bed of stromatolitic algal limestone, which occurs widely at this horizon in the Inner Hebrides (see above). An abundant shelly fauna, including the bivalves *Praemytilus*, *Unio* and *Tancredia*, occur in the fissile siltstones, thin limestones and sandstones of the lower part of Kildonnan Member at the type section on the east coast of Eigg (e.g. Hudson & Wakefield 1999). This section contains Hugh Miller's 'Reptile Bed' which has yielded sharks' teeth (*Hybodus*) and plesiosaur remains (*Plesiosaurus dolichoderius*) (Hudson 1966). Vertebrate remains have also been found on the north shore.

Outcrops of the cross-bedded Valtos Sandstone Formation extend from the east coast near Kildonnan, around the north of Eigg to the Bay of Laig, where several cycles of sedimentation are recognised. Particularly fine examples of carbonate concretions occur at the Bay of Laig (Figure 3-137; Figure 3-138; Figure 3-139; Figure 3-140; Figure 3-141; Figure 3-142).



Figure 3-137: Exposures of Valtos Sandstone Formation, north side of the Bay of Laig, Eigg.

beta version



Figure 3-138: Cross stratified Valtos Sandstone Formation sandstones, Bay of Laig, Eigg.



Figure 3-139: Carbonate concretions in pale sandstones of the Valtos Sandstone Formation at Bay of Laig, Eigg. Pole *ca*. 1 m long.



Figure 3-140: Large carbonate concretions in pale sandstones of the Valtos Sandstone Formation at Bay of Laig, Eigg. Pole *ca*. 1 m long.



Figure 3-141: Large carbonate concretions in pale sandstones of the Valtos Sandstone Formation at Bay of Laig, Eigg. Pole *ca*. 1 m long.

Proof version



Figure 3-142: Large carbonate concretions in pale sandstones of the Valtos Sandstone Formation at Bay of Laig, Eigg. Pole *ca*. 1 m long.

The section in Laig Gorge, SE of the Bay of Laig, contains exposures of both the Duntulm and Kilmaluag formations, as well as Cretaceous strata (see below). Thick limestones crowded with the oyster *Praeexogyra hebridica*, typical of the Duntulm Formation, give way to mudstones with only thin oyster shell beds. The mudstones grade upwards into calcareous mudstones and thin limestones of the Kilmaluag Formation, which contain an ostracod and conchostracan (*Antronestheria*) fauna. There are a few small exposures of both formations north of Laig Gorge, and both must be present beneath a cover of till and landslip in Cleadale, although they are progressively cut out eastwards by the unconformable base of the Upper Cretaceous strata and the Paleocene lavas.

On the foreshore at Camas Mòr, Muck, Mesozoic strata from the upper part of the Valtos Sandstone Formation are exposed. The beds include typical concretionary sandstones and grade up into highly fossiliferous limestones of the Duntulm Formation, in which shelly layers packed with *Praeexogyra hebrideca* are conspicuous. The lower part of the Kilmaluag Formation is seen in several small limestone outcrops totalling *ca*. 14 m in thickness (Figure 3-143). The higher beds are partly dolomitic, a feature first recognised from the mineralogy of the distinctive calc-silicate hornfelses adjacent to a large Paleocene gabbro dyke (Chapter 7). The fauna includes conchostracans of the genus Pseudograpta and the gastropod *Viviparus*.

Beta version



Figure 3-143: Sand-filled desiccation cracks in Kilmaluag Formation mudstone, Camas Mòr, Muck. Hammer *ca*. 30 cm long.

3.4.4 Mull and Ardnamurchan

Approximately 30 m of sandy limestone and calcareous sandstone of the Bearreraig Sandstone Formation are capped by 1 to 2 m of siltstone of the Great Estuarine Group on the east coast at Port na Marbh, SE Mull. Similar beds crop out fairly continuously beneath the lavas on the west limb of the Loch Don Anticline, and discontinuously on the east limb as far as Duart Bay. On Ardnamurchan, Middle Jurassic rocks are limited to massive sandstones and subordinate limestones of the Bearreraig Sandstone Formation exposed in screens amongst the Paleocene basalt sheets on Maol Buidhe and at Sròn Beag. Despite the effect of thermal metamorphism, typical Aalenian fossils have been obtained from these rocks (Richey & Thomas 1930).

3.5 'Upper' Jurassic (including the Callovian)

3.5.1 Introduction

An initially gentle marine transgression in the early Callovian marks a significant change away from the coastal-associated strata of the Middle Jurassic Great Estuarine Group. Thereafter, marine conditions were dominant, shallow marine-lagoonal at first (Staffin Bay Formation) and deeper, fully marine thereafter (Staffin Shale Formation). The principal developments of the Callovian, Oxfordian and Kimmeridgian strata occur on Skye on Strathaird and Trotternish; no strata younger than the Early Kimmeridgian have been reported from the district (Figure 3-144).

Beta version

The transgression began in the Callovian with the deposition of the fully marine Càrn Mòr Sandstone Member of the Staffin Bay Formation in the Strathaird section; this approximately equates with the Upper Ostrea Member and the Belemnite Sand Member in the Trotternish section, which have a marine to brackish water fauna and have yielded Callovian palynomorphs (Figure 3-147) (Riding 1992). A thin shell bed with *Neomiodon* and the larger bivalve *Isognomon*, with a dark shale matrix and overlain by further shales and shell-beds, some of which contain oysters, marks the base of the Upper Ostrea Member of the Staffin Bay Formation. It represents the gentlest of lagoonal transgressions.

The overlying, fully marine Staffin Shale Formation contains an abundant fauna, including ammonites that permit zonal correlation with the Upper Jurassic strata of England and the Boreal Realm of Greenland and the Arctic.

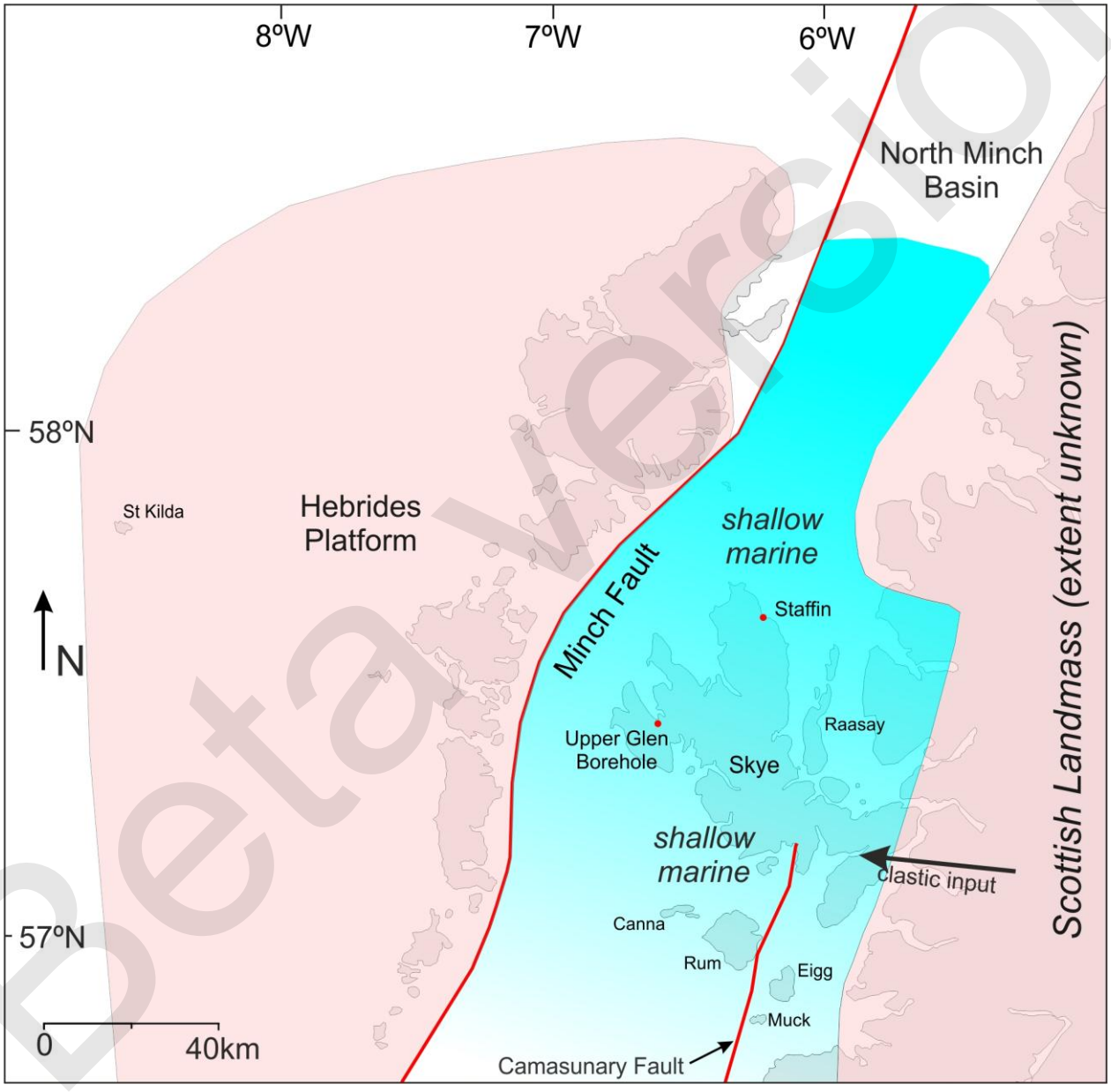


Figure 3-144: Late Jurassic (Kimmeridgian) palaeo-geographic map/interpretation (after Hudson & Trewin 2002).

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3.5.2 Skye

The youngest Jurassic strata in the district occur in a shallow anticline beneath the Paleocene lavas of Trotternish, although there the beds are largely obscured beneath landslips, and in Strathaird (Figure 3-145; Figure 3-146; Figure 3-147; Figure 3-148; Figure 3-149; Figure 3-150; Figure 3-151; Figure 3-152). There are small outcrops near Uig and in the Kilmaluag River, but the most extensive occurrences are on the shoreface at the west side of Staffin Bay, Trotternish. These beds, which are in the toe of the Quiraing Landslip, are not metamorphosed but are much faulted, cut by Paleocene minor intrusions, and commonly have steep dips as a consequence of the Pleistocene landslipping.

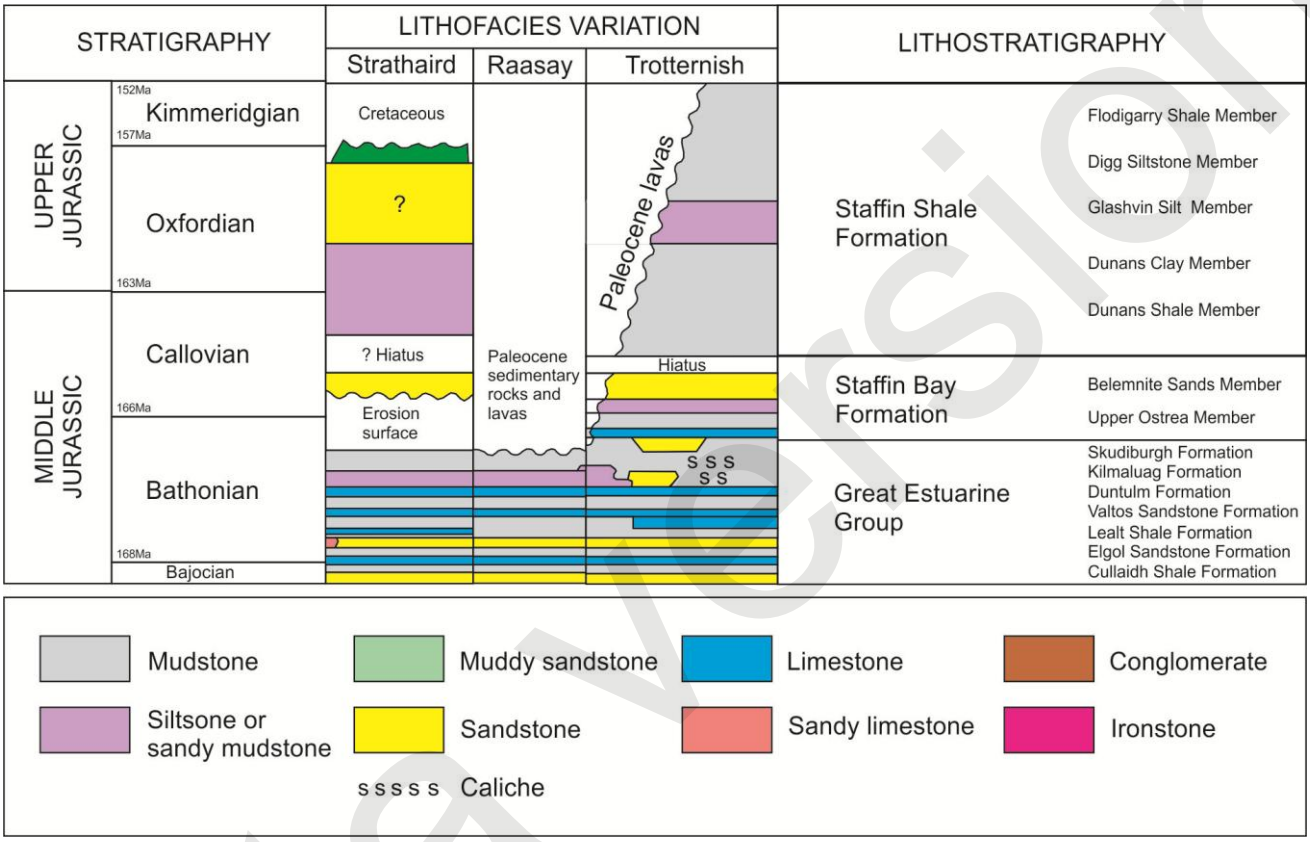


Figure 3-145: Lithostratigraphy of the Upper and Middle Jurassic on Skye and Raasay.

Lithologies present in the Trotternish section include shelly mudstones, siltstones and thin belemnite-bearing limestones of the Staffin Bay Formation (Lower Callovian) (Figure 3-147; Figure 3-148; Figure 3-149; Figure 3-150; Figure 3-151), and dark, silty claystones with subordinate silty sandstones and thin nodular limestone beds of the Staffin Shale Formation (Callovian to Lower Kimmeridgian) (Morton & Hudson 1995). The ammonites are mostly of Boreal provenance, but the occurrence of Tethyan forms is important in correlating the two faunal provinces of the European Jurassic.

Elsewhere, Oxfordian-Kimmeridgian mudstones, siltstones and sandstones are present near Strollamus, on southern Scalpay, and on the west side of Strathaird.

The Strathaird sequence is markedly coarser than the Trotternish section (Figure 3-146).

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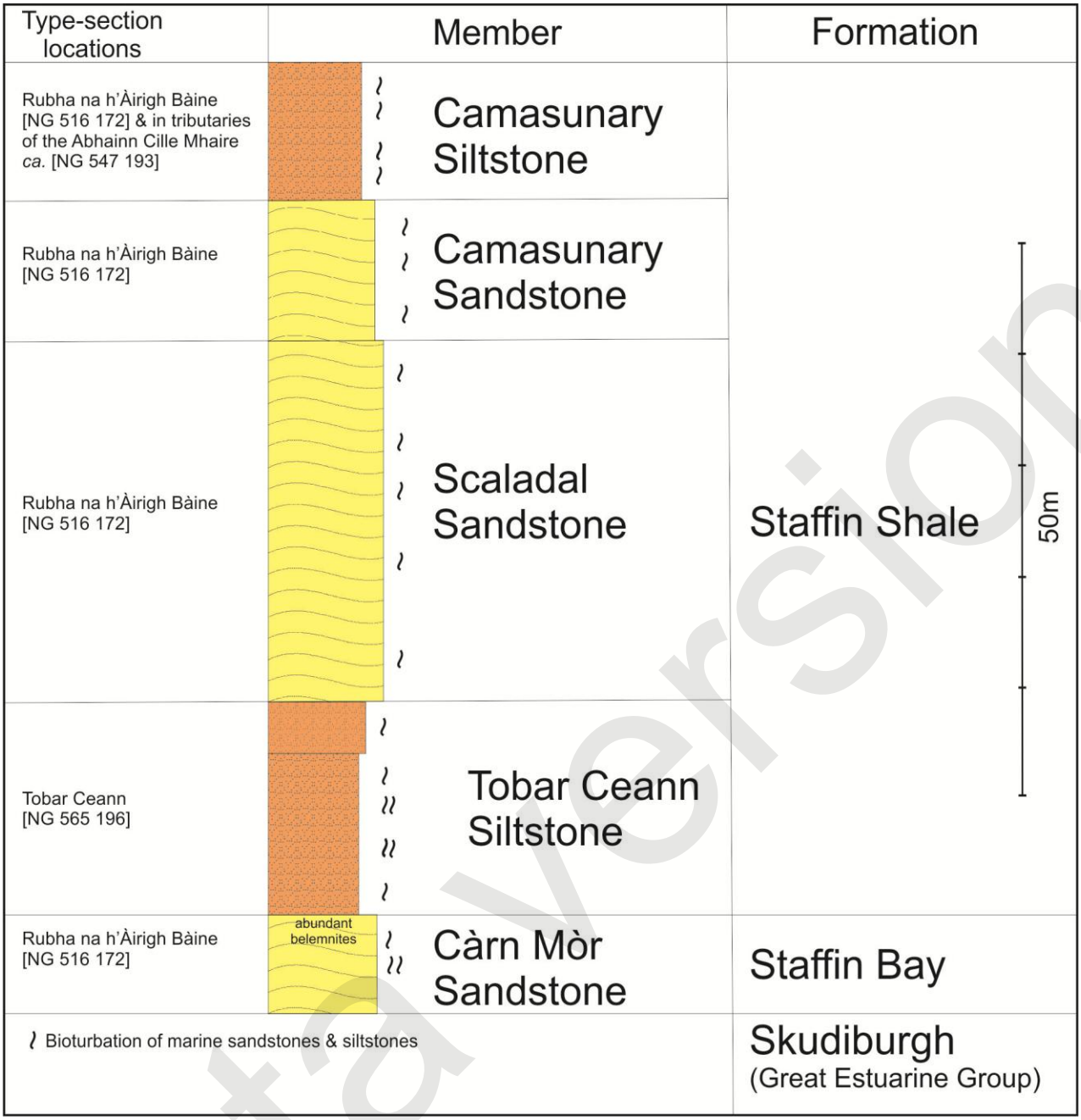


Figure 3-146: Lithology log for the Staffin Bay and Staffin Shale formations, Strathaird.

These clastic marine units are commonly rippled and bioturbated, with an ammonite, belemnite and brachiopod fauna, forming a more nearshore facies relative to the Trotternish sequence. They underlie Paleocene basaltic lavas and are typically indurated and altered.

Thin beds of altered tuff occur in the Staffin Shale Formation at Staffin Bay and may have been derived from volcanoes associated with the newly opened Rockall Trough (Knox 1977). An isopod crustacean has been recovered from beds of Oxfordian age at Staffin Bay (Feldmann *et al.* 1994).

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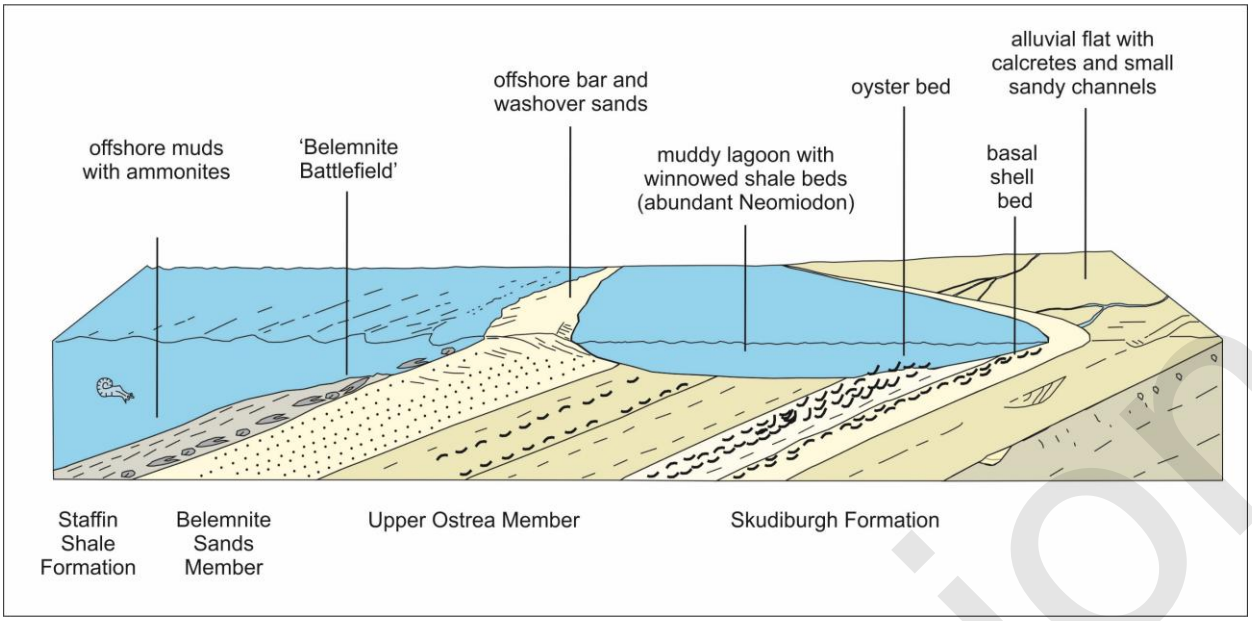


Figure 3-147: Staffin Bay and Staffin Shale formations facies interpretation for the Trotternish section, representing a transgression over the fluvial and alluvial Skudiburgh Formation at the top of the Great Estuarine Group (after Hudson & Trewin 2002). The Upper Ostrea Member indicates a first lagoonal transgression, followed by the shoreward migration of an offshore sand bar (the Belemnite Sands Member), and final flooding at the base of the Staffin Shale Formation, with numerous belemnites washed up the seaward slope of the bar. Not to scale.



Figure 3-148: Staffin Bay Formation shales on the coast at Digg at the northern end of Staffin Bay. Pole *ca.* 1 m long.

Draft version



Figure 3-149: Annotated Google Earth© image indicating locations of geological maps and sections on the Staffin coastline, Trotternish.

Beta version

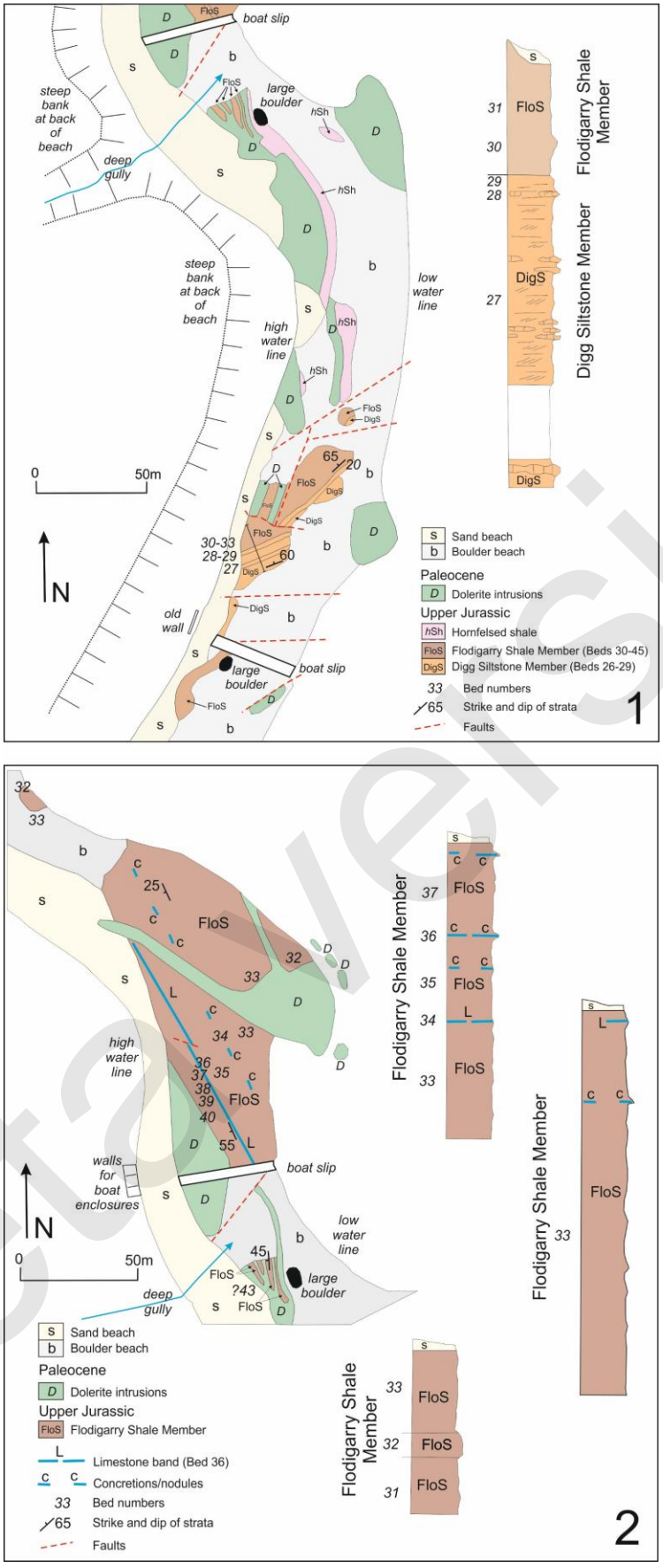


Figure 3-150: Geological maps and sections for Staffin Shale Formation sequences, Staffin, Trotternish.

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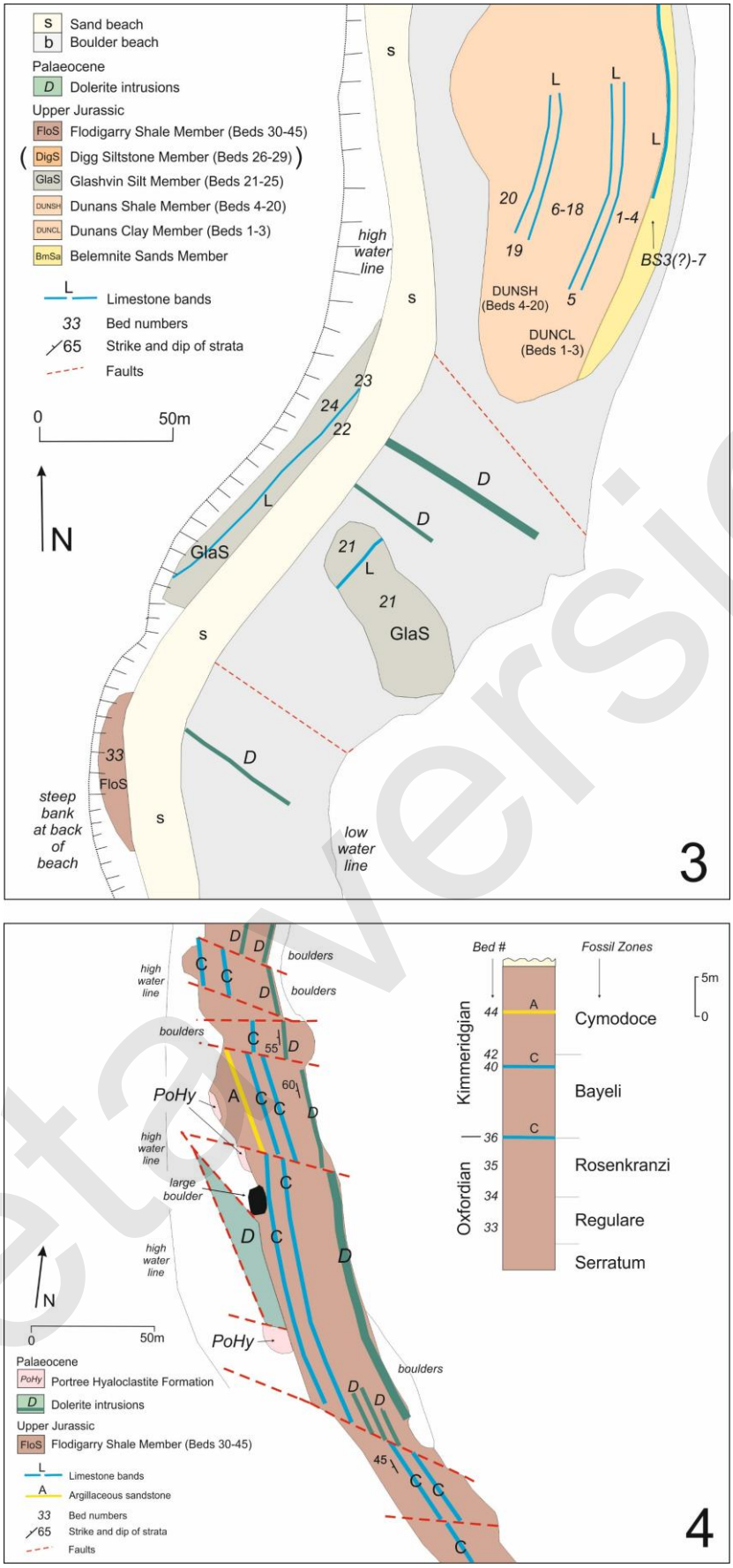


Figure 3-151: Geological maps and sections for Staffin Shale Formation sequences, Staffin, Trotternish.

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Figure 3-152: (a) whorl section of a mineralized ammonite, coin *ca.* 20 mm across; (b) belemnites, coin *ca.* 20 mm across; (c) bivalve, coin *ca.* 20 mm across.; and, (d) carbonate-cemented layer (concretion or 'cementstone'), pole *ca.* 1 m long. All Staffin Bay Formation, Digg, Trotternish, Skye.

3.5.3 Eigg

The Staffin Shale Formation is exposed among boulders on the shoreface between Clach Alisdair and the Bay of Laig. It consists of *ca.* 35 m of soft mudstone with limestone beds, and ranges from the Callovian *Quenstedtoceras lamberti* Zone to the Oxfordian *Cardioceras cordatum* Zone.

3.5.4 Mull

A small outcrop of baked blue shale just west of Duart Bay, SE Mull, has yielded ammonites and other fossils of Kimmeridgian age (*mutabilis* Zone).

Beta version

3.6 Cretaceous

3.6.1 Introduction

In the Inner Hebrides, Upper Cretaceous (Cenomanian to Maastrichtian) rocks are best known from Mull and Skye, but also occur on adjacent islands, and significantly on Morvern on the Scottish Mainland. Access to many of the exposures is either difficult or elusive. These scattered outcrops comprise mainly, but not exclusively, of chalky limestones, mudstones, glauconitic siltstones and sandstones, and, a highly distinctive, near monomineralic, quartz sandstone (Mortimore *et al.* 2001; Mortimore & Long 2024) (Figure 3-153; Figure 3-154; Figure 3-155). These lithologies and their sparse fossil content indicate low-energy, open-marine shelf conditions, with slow sediment accumulation and extensive biogenic carbonate production; as an indicator of conditions of deposition; glauconite is an authigenic mineral typically restricted to marine sandstones. The chalky facies records deposition well below wave base, under stable, oxygenated water columns and low terrigenous input, consistent with global Late Cretaceous high sea levels. Thicknesses of the disparate sections preserved are typically up to *ca*. 20 m.

The Upper Cretaceous successions of the Inner Hebrides rest unconformably predominantly on Jurassic strata, commonly with evidence of condensation, omission surfaces and hard grounds, reflecting long intervals of non-deposition. Fossil assemblages, where preserved, are dominated by planktonic and nektonic faunas, supporting interpretation of fully marine conditions and open ocean connectivity.

In Morvern, the Cretaceous record is lithologically distinct and of particular significance (Figure 3-156). The Lochaline White Sandstone Formation, preserved in a fault-bounded basin, represents an ultra-clean, well-sorted, quartz sandstone deposited in a nearshore to shallow-marine setting. Its extreme textural maturity reflects prolonged sediment reworking under high-energy conditions and low sediment supply. Although volumetrically limited, this unit demonstrates that marginal siliciclastic systems persisted locally along the Cretaceous shelf. The Lochaline White Sandstone Formation is overlain or associated with marine mudstones, indicating rapid lateral facies transitions between shallow and deeper marine environments. These relationships emphasise the strong control exerted by local basin geometry and inherited topography on Cretaceous sedimentation.

The Cretaceous record, characterised by thin stratigraphic packages, widespread unconformities and lateral discontinuity, contrasts sharply with the thicker Jurassic successions, below (Figure 3-154). This most likely reflects a tectonic regime dominated by post-rift thermal subsidence, with reduced fault activity but pronounced susceptibility to later uplift and erosion. Tectonic activity may have occurred in the Late Cretaceous; on Skye; some of the movement on the Camasunary-Skerryvore Fault post-dates the Cretaceous deposits, and on Mull late movements on the Great Glen Fault most likely affected the Cretaceous rocks at Torosay (Mortimore *et al.* 2001).

Much of the Cretaceous succession was subsequently disrupted or removed during Paleocene uplift and magmatism associated with the opening of the NE Atlantic (Chapters 4 & 5).

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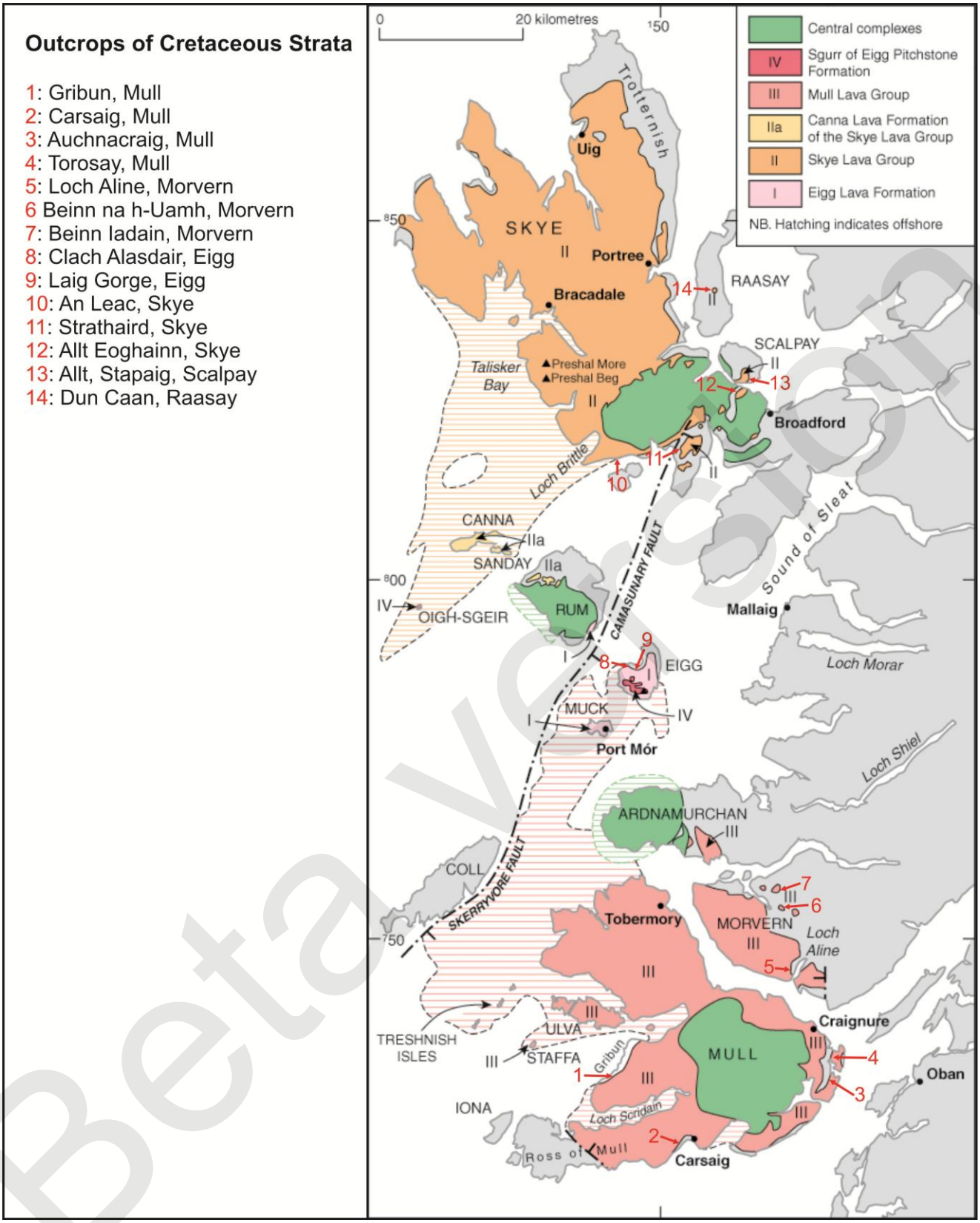


Figure 3-153: Simplified geological map showing locations of Upper Cretaceous strata in the Hebridean Igneous Province.

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Locality	Litho-stratigraphy	Thickness (m)	Lithologies	Underlying strata
Arran: *Central Arran Ring-complex*	?	3 (max)	limestone, white sandstone	*remanié* masses in ring-complex
Mull: *Gribun*	Gribun Chalk Fm Coire Riabhach Phosphatic Fm Loch Aline White Sandstone Fm Morvern Greensand Fm	15	chalk, white sandstone, glauconitic sandstone	New Red Sandstone to Blue Lias Triassic to Hettangian
Mull: *Torosay*	?Gribun Chalk Fm	3	chalk	Pabay Shale Fm Sinemurian
Mull: *Auchnacraig*	Gribun Chalk Fm Loch Aline White Sandstone Fm Morvern Greensand Fm	5	glauconitic sandstone	Lias Group to Bearreraig Sandstone Formation Hettangian to Bajocian
Mull: *Carsaig*	Loch Aline White Sandstone Fm Morvern Greensand Fm	13	glauconitic sandstone, ?chalk	Scalpay Sandstone Fm Pliensbachian to Toarcian
Morvern: *Beinn Iadain*	See Figure 7 for details	22	chalk, white sandstone, glauconitic sandstone	Moine psammite and pelite. Blue Lias to south Sinemurian
Morvern: *Loch Aline*	Loch Aline White Sandstone Fm Morvern Greensand Fm	20	white sandstone, glauconitic sandstone	Blue Lias to Pabay Shale Fm Hettangian to Sinemurian
Ardnamurchan: *East of Bheinn Buidhe*	-	5	*remanié* chalk flint and sand grains	*In* Paleocene mudstone on Moine gneisses
Ardnamurchan: *East of Ben Haint*	?Loch Aline White Sandstone Fm	1	silicified pure quartz sand	Moine psammite and pelite
Eigg: *Laig Gorge*	Strathaird Limestone Fm (Laig Gorge Sandstone Mbr)	5	chalk, sandstone and conglomerate	Kilmaluag Formation Bathonian
Eigg: *Clach Alasdair*	Strathaird Limestone Fm (Clach Alasdair Conglomerate Mbr)	<1	silicified sandstone, glauconitic sandstone	Staffin Shale Fm Oxfordian
Eigg: *Allt Ceann a' Gharaidh*	?	1.5	glauconitic sandstone, flint conglomerate	Valtos Sandstone Fm Bathonian
Skye: *Strathaird*	Strathaird Limestone Fm	3	chalk, gritty sandstone	Staffin Shale Fm Oxfordian
Skye: *Strollamus*	Strathaird Limestone Fm	3	chalk	Staffin Shale Fm Oxfordian
Skye: *Soay Sound*	Morvern Greensand Fm	5	red sandstone, glauconitic sandstone, cherty sandstone	Broadford Beds, Hettangian to Sinemurian
Skye: *Waterstein Head*	?	?	glauconitic sandstone	?Duntulm Fm Bathonian
Scalpay: *Allt Stapaig*	Strathaird Limestone Fm in part	5	sandstone, gritty calcareous sandstone	Staffin Shale Fm Oxfordian

Figure 3-154: Summary of Upper Cretaceous strata in the Inner Hebrides and Arran.

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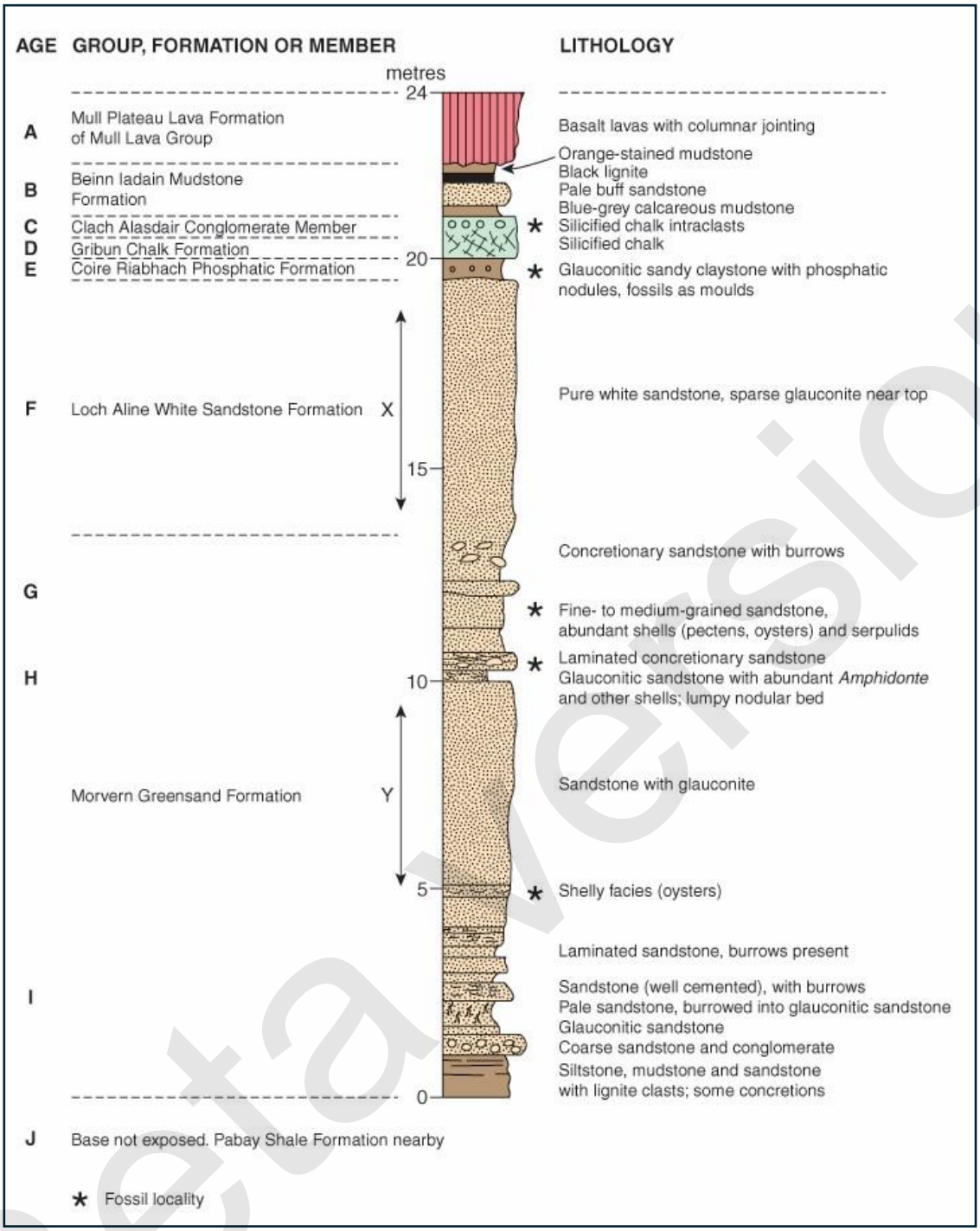


Figure 3-155: Upper Cretaceous strata of the Inner Hebrides Group, exposed on the SE side of Beinn Iadain, Morvern (after Mortimore *et al.* 2001, figure 6.29). The thick sandstones of the Loch Aline White Sandstone and Morvern Greensand formations are obscured beneath steep grassy slopes at X and Y, respectively. Age of deposits: A, lavas of Paleocene age; B, Beinn Iadain Formation, generally assumed to be of Paleocene age; C, Upper Cretaceous; D, Judd (1878) recognised Belemnitella (Campanian) from the chalk, but the exact horizon is uncertain: E, Sponges dated as Santonian; F, undated, generally considered to be Turonian (but may be Cenomanian, Braley 1990); G, probably Upper Cenomanian; H, probably Middle Cenomanian (compared with better dated site in Northern Ireland); I, uncertain, possibly Lower Cenomanian; J, Lias and Permo-Triassic rocks in track section leading to Beinn Iodain.

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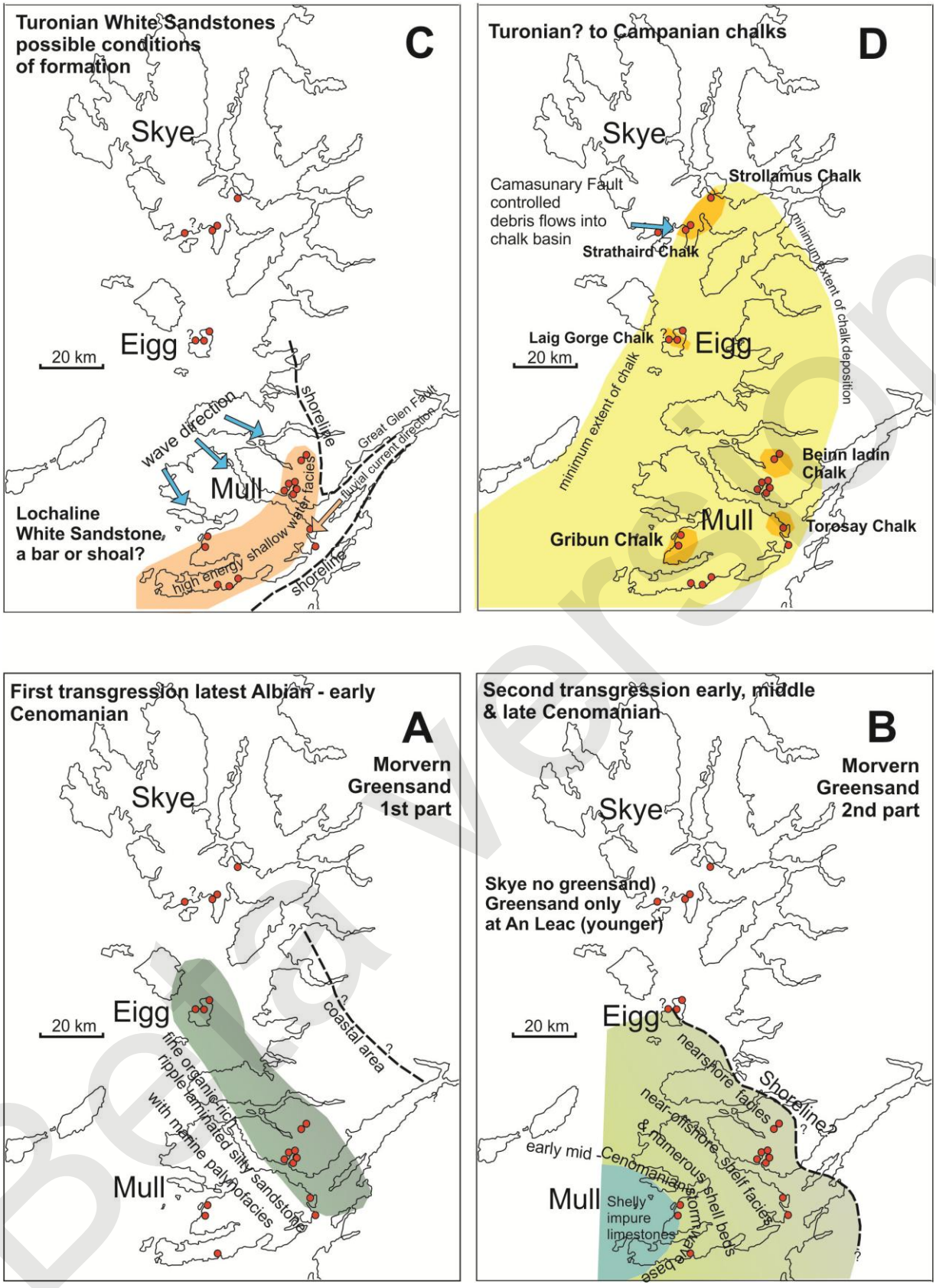


Figure 3-156: Possible palaeogeography interpretations for the Late Cretaceous in the Inner Hebrides area (Albian-Campanian). (a) & (b) Cenomanian Morvern Greensand Formation; (c) Turonian Lochaline White Sandstone Formation; and, (d) Santonian-Campanian Gribun and Beinn Iadian chalks. [Figure courtesy of Rory Mortimore, from Mortimore & Long 2024].

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Thermal alteration of the Upper Cretaceous rocks by the overlying Paleocene lavas contributes to making precise dating of the deposits difficult, since microfossils and spores have commonly been destroyed. Another common feature is the 'silicification' of much of the chalk, whereby the original calcareous materials (foraminifera, coccoliths, bioclastic debris etc.) are now composed of microcrystalline silica.

The Cenomanian age of glauconitic sandstones at the base of the successions in Mull and Morvern is firmly established (Lowden *et al.* 1992), but the age of overlying beds is less certain (Figure 3-155). At the top of the succession, the Beinn Iadain Mudstone Formation and part of the Clach Alasdair Conglomerate Member, may well be partly of Paleocene age (Mortimore *et al.* 2001), although Hancock (2000) suggests a Maastrichtian age for these beds on Mull, which he termed the Gribun Conglomerate Formation (see below). The brown mudstones at the top of the pre-lava sequences have generally been interpreted as decomposed ash, deposited immediately prior to the main basaltic lava volcanism (e.g. Richey 1961).

The presence of rounded 'millet seed' sand grains in many of the Hebridean Cretaceous rocks, together with the silica-cementation of some beds (interpreted as 'silcretes') and the presence of silicified chalk led to the suggestion that desert conditions prevailed around the chalk seas (Bailey 1924), although others have disagreed with this interpretation (see Mortimore & Long 2024). A study of the silicification within the Lochaline White Sandstone Formation at the Lochaline Mine, Morvern, shows that the silica-cementation, which has resulted in frosted and faceted sand grains of all sizes, is restricted to certain well-defined beds, suggesting that it was caused by groundwater circulation, concentrated along highly permeable layers (Lowden *et al.* 1992).

The age of the Lochaline White Sandstone Formation has not been determined with any certainty due to a lack of diagnostic fossils, although a Turonian age is the best fit based upon its position in the overall stratigraphy (Figure 3-155) (Mortimore *et al.* 2001).

The presence of lignite and lateritic mudstone overlying the chalk is taken by Mortimore *et al.* (2001) to suggest hot, wet conditions towards the end of Cretaceous time, which would have required a dramatic and sudden change in climate if this had been preceded by desert conditions.

The most complete successions of Upper Cretaceous rocks in the district are found at Gribun, Mull (over 15 m thick), and on Ben Iadain, Morvern (over 21 m thick) (Mortimore *et al.* 2001 and references therein). Offshore deposits of Cretaceous age are very limited (Fyfe *et al.* 1993).

3.6.2 Skye

Three small outcrops of distinctive limestone, sandstone and conglomerate occur immediately below the Paleocene lavas around Beinn Leacach on Strathaird (e.g. Hudson 1983). Two of these outcrops include up to 2 m of blue, sandy limestone containing fragments of the bivalves *Inoceramus* and *Pecten*. The limestone, together with the underlying coarse-grained calcareous pebbly and gritty sandstones (*ca.* 1 m thick), have been assigned to the Upper Cretaceous (Turonian) Strathaird Limestone Formation. The formation also crops out in the Allt Eoghainn, west of Creag Strollamus, where a 3 m thick bed of white limestone overlies Oxfordian strata (Figure 3-157).

On the north side of Soay Sound, up to 16 m of red and green glauconitic sandstones, capped by a hard sandstone with cherty concretions, have yielded microfossils of probable Cretaceous age, and have been assigned to the Cenomanian Morvern Greensand Formation. Chaotic assemblages of clasts and slabs of Cretaceous sandstone and chert are found hereabouts; they formed in pre-Paleocene times, when Cretaceous strata collapsed into a cavity formed by solution-weathering of the underlying Lower Jurassic limestones.

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Glauconitic sandstones recovered from landslips below the Paleocene lava cliffs of Waterstein Head in NW Skye are also most likely Cretaceous in age.



Figure 3-157: Upper Cretaceous calcareous sandstones and limestones exposed in the Allt Eoghainn (with trees, below power lines) and a parallel unnamed stream to the east (nearest), west of Creag Strollamus in Strath, Skye.

3.6.3 Scalpay and Raasay

A Cretaceous sequence, *ca*. 5 m thick, underlies Paleocene basaltic lavas in the Allt Stapaig valley in SE Scalpay, north across Caolas Scalpay from the Strollamus outcrops on Skye (see above) (Figure 3-158). The upper half of the succession consists of sandstones with a bed of chert nodules at the base. Underlying the sandstone is limestone with cherty masses and, at the base, *ca*. 0.5 m of hard calcareous gritty sandstone containing the bivalves *Exogyra* and *Pecten asper*. The lower beds may be equated with the Strathaird Limestone Formation.

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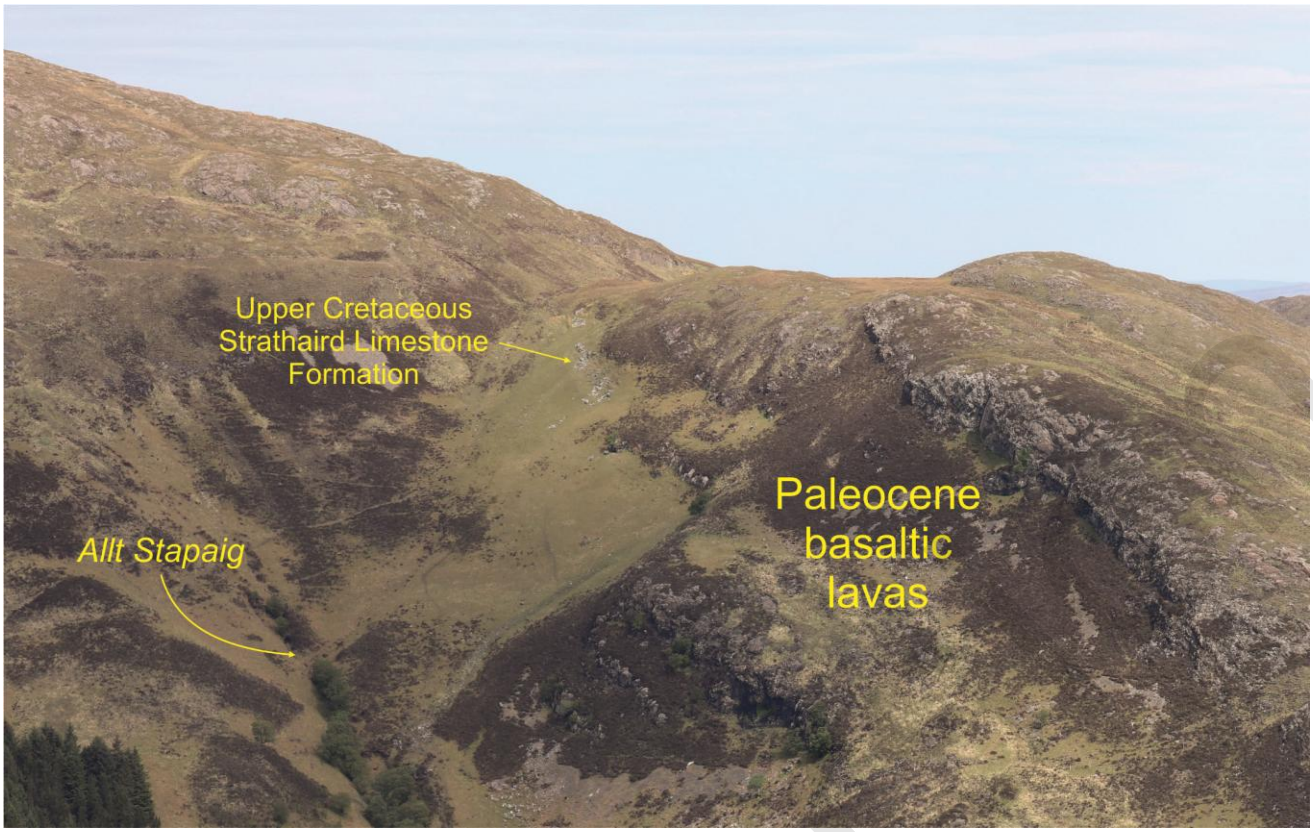


Figure 3-158: Exposure of the Upper Cretaceous Strathaird Limestone Formation, Allt Stapaig valley, SE Scalpay. View towards the north from Creag Strollamus, Skye.

A poorly exposed thin bed of glauconitic sandstone on the western side of Dùn Caan, Raasay, is probably of Cenomanian age (Lee 1920).

3.6.4 Eigg

At Laig Gorge on the west side of Eigg, *ca.* 2.5 m of conglomerate fines upwards into coarse- and fine-grained sandstones, forming the Laig Gorge Sandstone Member. Rounded pebbles in the conglomerate include quartzite, vein-quartz and phosphorite (which may contain ooidal chamosite). Hudson (1960) has recorded a derived Oxfordian ammonite, *Cardioceras* (*Scarburgiceras*) from these beds. The overlying 2.5 m thick beds consist of sandy limestones overlain by flint-free micritic limestones. The limestones contain a planktonic fauna, including the foraminifera *Hedbergella praehelvetica,* which indicates an early to mid-Turonian age (Figure 3-156). Rare fragments of *Inoceramus* bivalves also occur. At Clach Alasdair, west of the Bay of Laig, glauconitic sandstones and silicified flint conglomerates form a layer less than 1 m thick between calcareous siltstones of the Staffin Shale Formation and the overlying Paleocene lavas. These beds form the Clach Alasdair Conglomerate Member and, together with the Laig Gorge succession, are assigned to the Strathaird Limestone Formation. Their Cretaceous age has been determined from a poorly preserved microfauna (Harker 1908). In northern Eigg, exposures in the Allt Ceann a' Gharaidh comprise *ca.* 50 cm of coarse conglomerate with pink to grey, possibly baked, flint fragments up to 10 cm across, overlain by white sandstone containing rare glauconite; wedges of chalk conglomerate are present, and lignite occurs towards the top of the section (Mortimore *et al.* 2001). These deposits overlie sandstones of the Valtos Sandstone Formation and are capped by Paleocene lavas.

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3.6.5 Ardnamurchan

No *in situ* fossiliferous Cretaceous deposits have been recorded from this area but *remanié* flint pebbles, rounded quartz grains and a shark's tooth (*Oxyrhina (?)mantelli*) have been recorded from mudstones beneath Paleocene lavas on the SE side of Bheinn Buidhe in eastern Ardnamurchan (Richey & Thomas 1930). A bed of highly indurated pure quartz sandstone, *ca*. 1 m thick, overlies Moine psammite and underlies red mudstone (possibly of the Beinn Iadain Mudstone Formation) and Paleocene lavas, *ca*. 2 km east of Ben Hiant. This may be the equivalent of the indurated sandstone of Cretaceous age that occurs on the north side of Morvern (see below).

3.6.6 Mull

The nature of the 'outcrop(s)' of Cretaceous strata at Gribun in west-central Mull, along a *ca*. 6 km section between Balmeanach and Clachandu, is complicated: many are not truly *in situ,* being 'located' within landslipped masses (Figure 3-159) (Chapter 13). Consequently, the structural and stratigraphic relationships of the many disparate exposures are difficult to determine. Further complications are the near-constant, present-day erosion of detritus from the overlying cliffs composed of Paleocene lavas, which significantly masks the soft Cretaceous rocks, together with the rampant vegetation on these steep slopes. Consequently, exposure of the Cretaceous rocks has changed since they were first described by Judd in 1878 (Mortimore *et al*. 2001), for example, material on the beach at Clachandu is no longer exposed. The main exposures are on the landward (east) side of the road at Gribun. Mortimore *et al*. (2001) describe these exposures in detail, including specifics on how to locate them (Figure 3-160; Figure 3-161).

Historically, certain of the exposures located within the Gribun landslips were referred to by Judd (1878) as 'boulders' (Figure 3-160; Figure 3-161). The orientation of the stratification of some of these boulders is random, which can be attributed to their displacement (including rotation) during the Quaternary landslipping events and further, subsequent (recent) slumping. However, their original 'way up' can be determined from an overall understanding of the regional stratigraphy of the Upper Cretaceous sequences (see above and below). One advantage of present-day differential weathering of these exposures is to make their fossil content more conspicuous (see below).

Due to the restrictive nature of the Gribun exposures, there are still some uncertainties about the age of these deposits, including the possibility that they are reworked material within what is, essentially, Paleocene strata. As such, they may be *remanié* deposits within the volcanic-dominated Paleocene sequence (see below).

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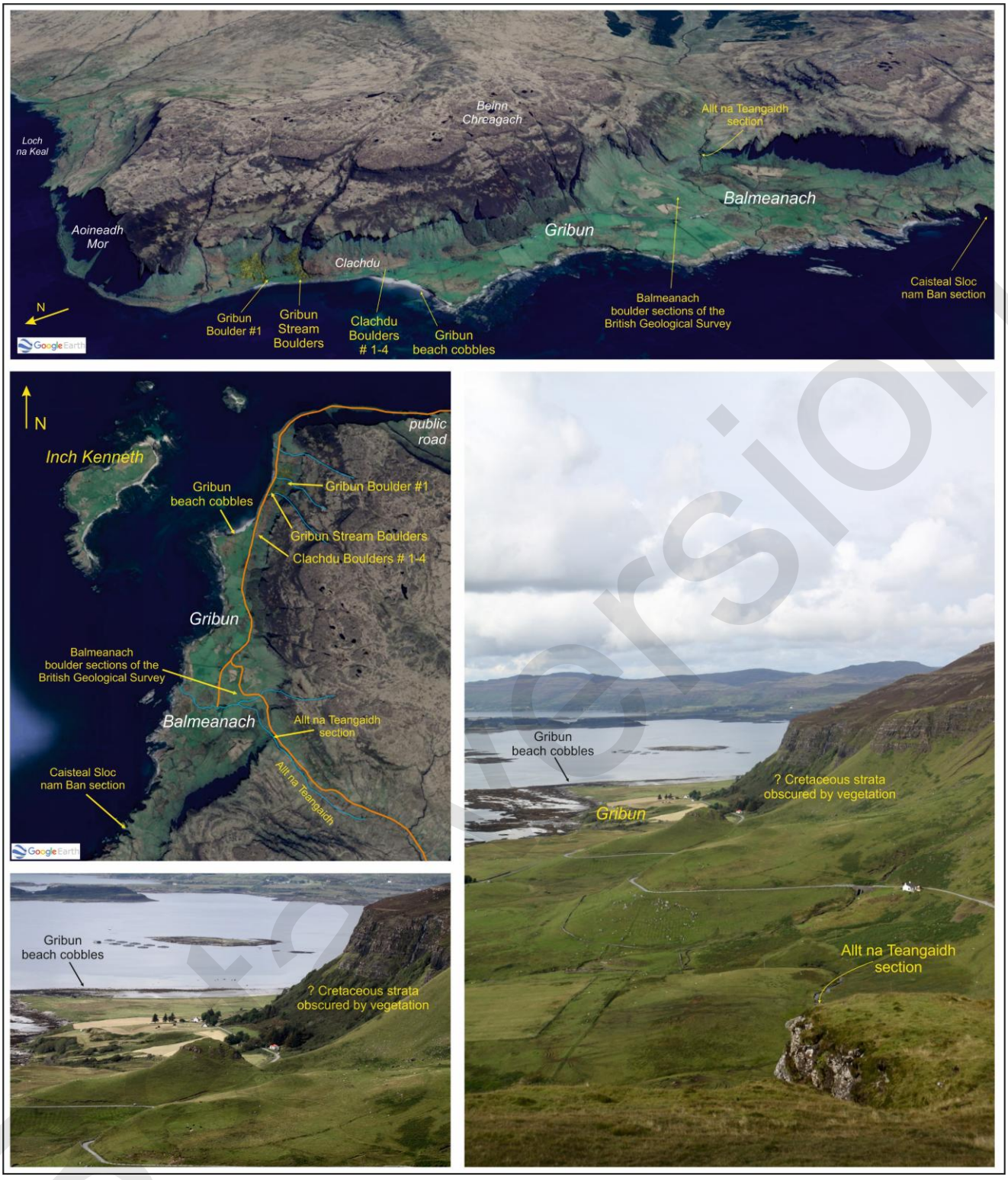


Figure 3-159: Annotated Google Earth© images and field photographs of the Gribun area, west-central Mull, indicating the locations of exposures of Upper Cretaceous strata.

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Figure 3-160: Clachandu Cottage Boulders, Gribun, west-central Mull. [Photographs courtesy of Rory Mortimore]

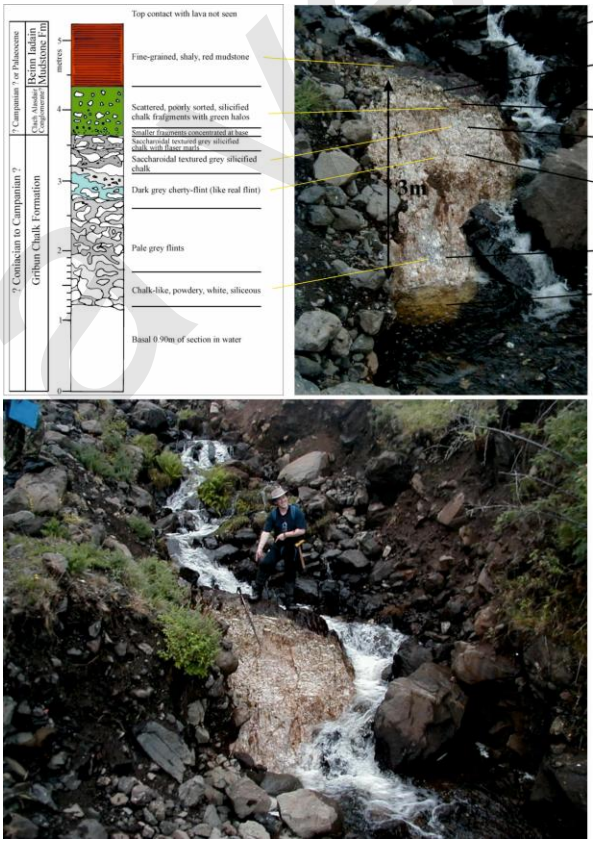


Figure 3-161: Gribun Stream Boulder, west-central Mull, and 'stratigraphic log'. [Photographs and log courtesy of Rory Mortimore]

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The only location in west-central Mull where the Cretaceous sequence appears to form a relatively coherent section, not significantly affected by landslipping events, is in the Allt na Teangaidh, south of Gribun, which can usefully be used as a 'reference' section (Figure 3-162; Figure 3-163**;** Figure 3-164**;** Figure 3-165).

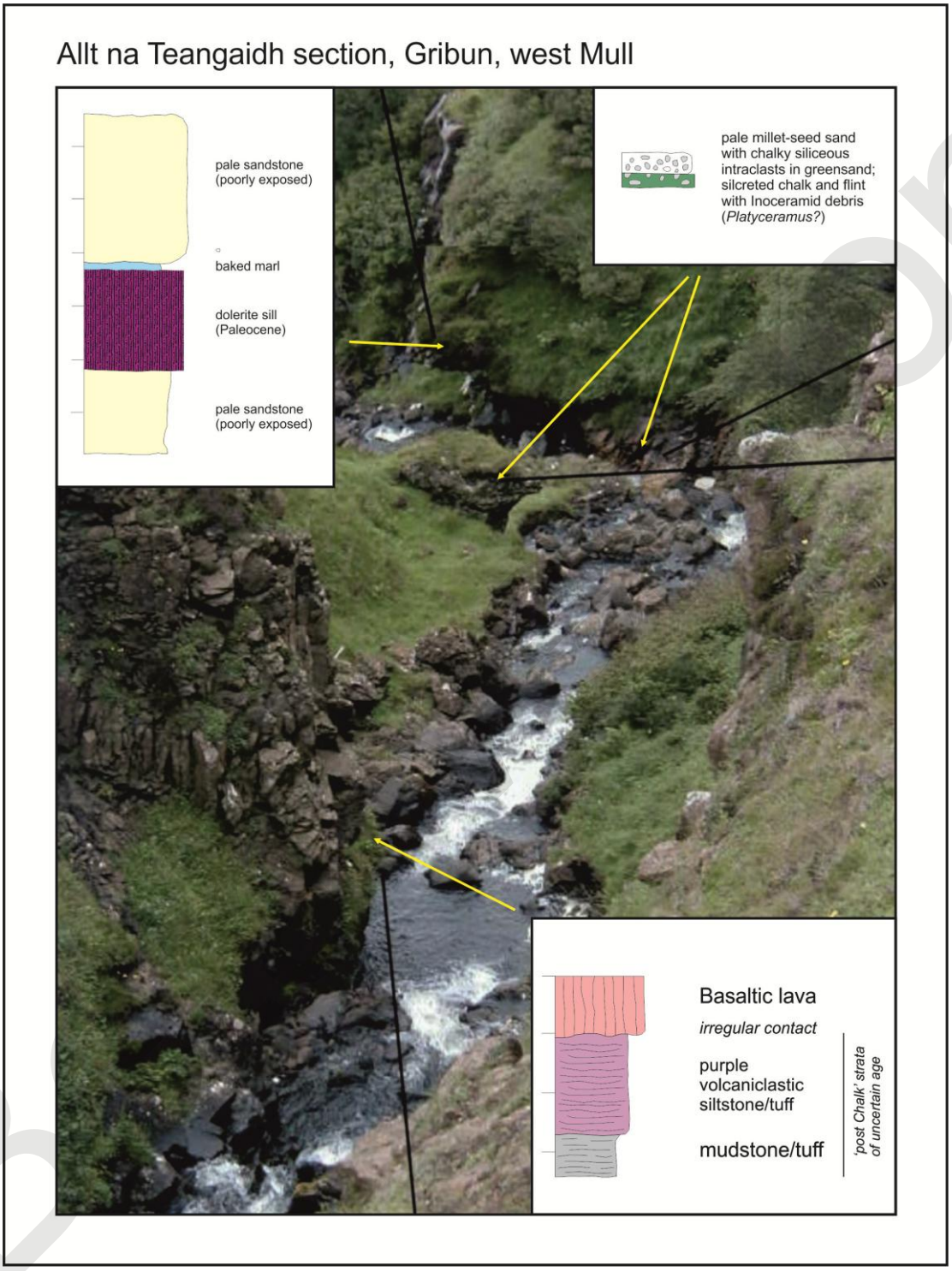


Figure 3-162: Upper Cretaceous section in the Allt na Teangaidh, Gribun, west-central Mull. [Photograph courtesy of Rory Mortimore]

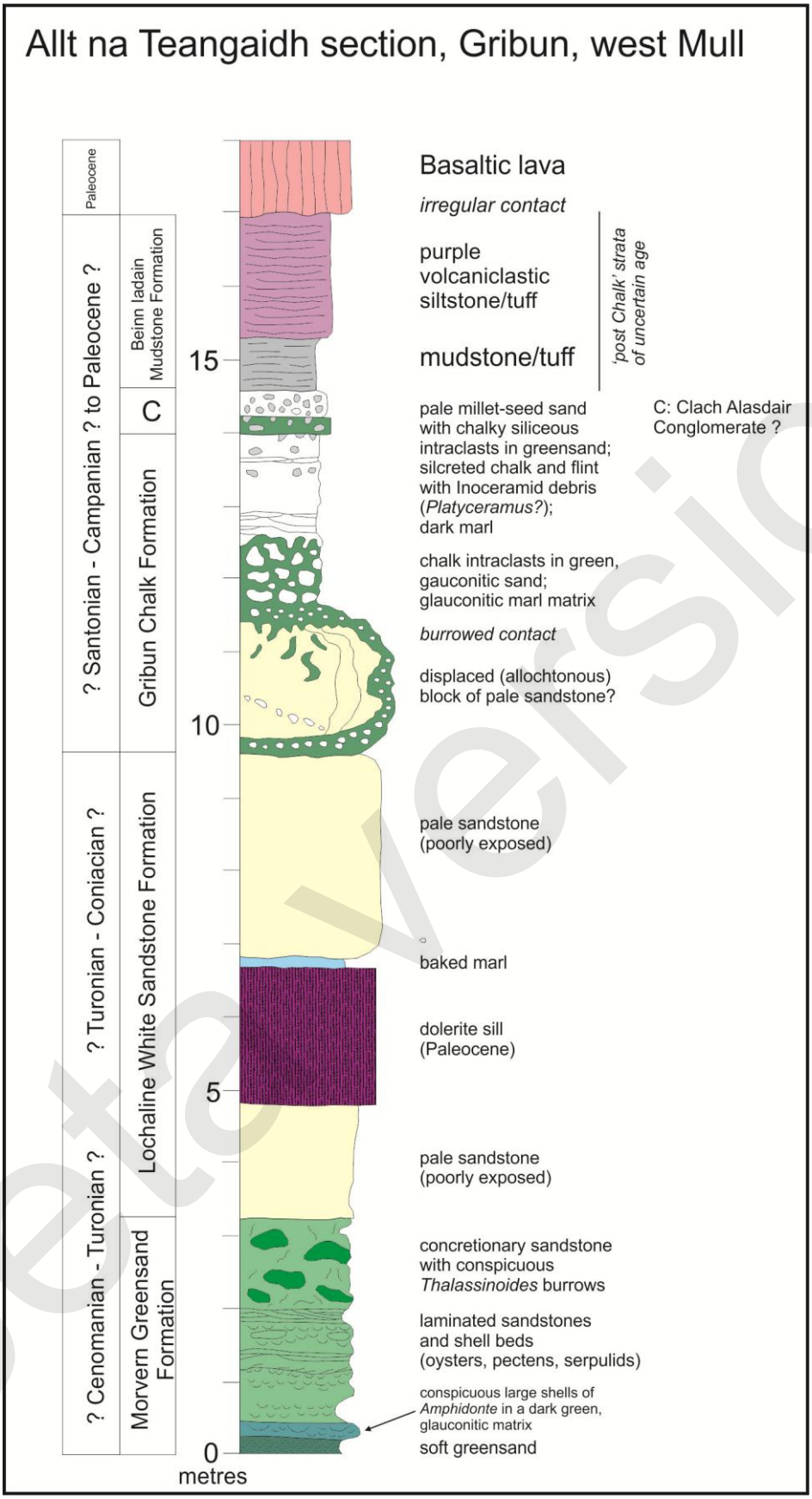


Figure 3-163: Stratigraphic log of Upper Cretaceous section, Allt na Teangaidh, west-central Mull (after Mortimore & Long 2024).

Beta version



Figure 3-164: Boundary between Gribun Chalk Formation overlying glauconitic sand with chalk intraclasts, Allt na Teangaidh, Gribun, west-central Mull. Coin *ca.* 24 mm across. [Photograph courtesy of Rory Mortimore]



Figure 3-165: Morvern Greensand Formation, with concretionary facies with *Thalassinoides* burrows at top of exposure, Allt na Teangaidh, Gribun, west-central Mull. [Photograph courtesy of Rory Mortimore]

In summary, integrating observations from the Gribun exposures and the Allt na Teangaidh section, Cenomanian glauconitic sandstones (*ca*. 6 m thick) are overlain by *ca*. 3 m of white sandstone and *ca*. 3 m of silicified chalk with flints (possibly Santonian) (Figure 3-163). The chalk is overlain by a breccia containing angular pebbles and cobbles of silicified chalk, sandstone with chert nodules, and *ca*. 2 m of weakly bedded, red mudstone. The beds above the chalk have been formally designated to the Gribun Conglomerate Formation by Hancock (2000), but have been equated with the Clach Alasdair Conglomerate Member and the Beinn Iadain Mudstone Formation by Mortimore *et al*. (2001) (Figure 3-163). The succession is overlain by Paleocene basaltic lavas. A rich bivalve fauna occurs in the glauconitic sandstone, including *Rhynchonella*, *Exogyra conica*, and *Pecten asper* (Figure 3-166). *Ostrea* and *Pecten* occur in the chalk.



Figure 3-166: *Rhynchostrean* oyster shells in the Balmeanach Boulders, Gribun, west-central Mull. [Photograph courtesy of Rory Mortimore]

Glauconitic sandstones (Morvern Greensand Formation) and pale (quartz) sandstones (the Lochaline White Sandstone Formation) occur at Carsaig in south Brolass, SW Mull, where they are up to *ca*. 13 m thick (Figure 3-167; Figure 3-168; Figure 3-169).



Figure 3-167: Upper Cretaceous section, gully west of Carsaig, south Brolass, SW Mull (after Mortimore & Long 2024). [Photograph courtesy of Rory Mortimore]

Beta version



Figure 3-168: *Thalassinoides* burrows in boulder of Morvern Greensand Formation strata, Carsaig, south Brolass, SW Mull. Hand for scale. [Photograph courtesy of Rory Mortimore]



Figure 3-169: *Thalassinoides* burrows in boulder of Morvern Greensand Formation strata, Carsaig, south Brolass, SW Mull. Hammer *ca*. 40 cm long. [Photograph courtesy of Rory Mortimore]

Portions of the complete Upper Cretaceous sequence crop out at Auchnacraig and Torosay, south of Loch Don in SE Mull (Figure 3-154; Figure 3-155).

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Interbedded with the basaltic lavas of the Paleocene Staffa Lava Formation in south Brolass, SW Mull (Chapter 6), thick, cross stratified conglomerates are dominated by large clasts of flint, some with the appearance of being almost whole nodules/concretions, together with abundant fragments of flint. These flint-rich deposits, interbedded with Paleocene basaltic lavas, composed of material of presumed Cretaceous age, are interpreted as a *remanié*. The so-called Pulpit Rock at Malcolm's Point on the south coast of Brolass, is the most spectacular exposure of these strata (see *Front Cover*). Other good examples of similar coarse clastic units with fragments of flint occur in the sedimentary sequence at Ardtun, part of the 'Ardtun Leaf Beds', on the south coast of Loch Scridain (Chapter 6).

3.6.7 Morvern

Siliceous and glauconitic sandstones, characterised by species of *Exogyra* and *Pecten* bivalves, underlie the Paleocene lavas of Morvern. At the Lochaline sandstone mine there are excellent exposures of a white sandstone (*ca.* 15 m thick), formed from pure quartz sand that is generally poorly cemented, except in hard, silica-cemented bands (see above) (Figure 3-170; Figure 3-171; Figure 3-172; Figure 3-173; Figure 3-174): this is the Lochaline White Sandstone Formation. The active mine is an important source of high-grade glass-sand (Chapter 14).



Figure 3-170: Abandoned entrance (Adit #7) to the Lochaline sand mine, Lochaline, Morvern. [Photograph courtesy of Peter Bond]

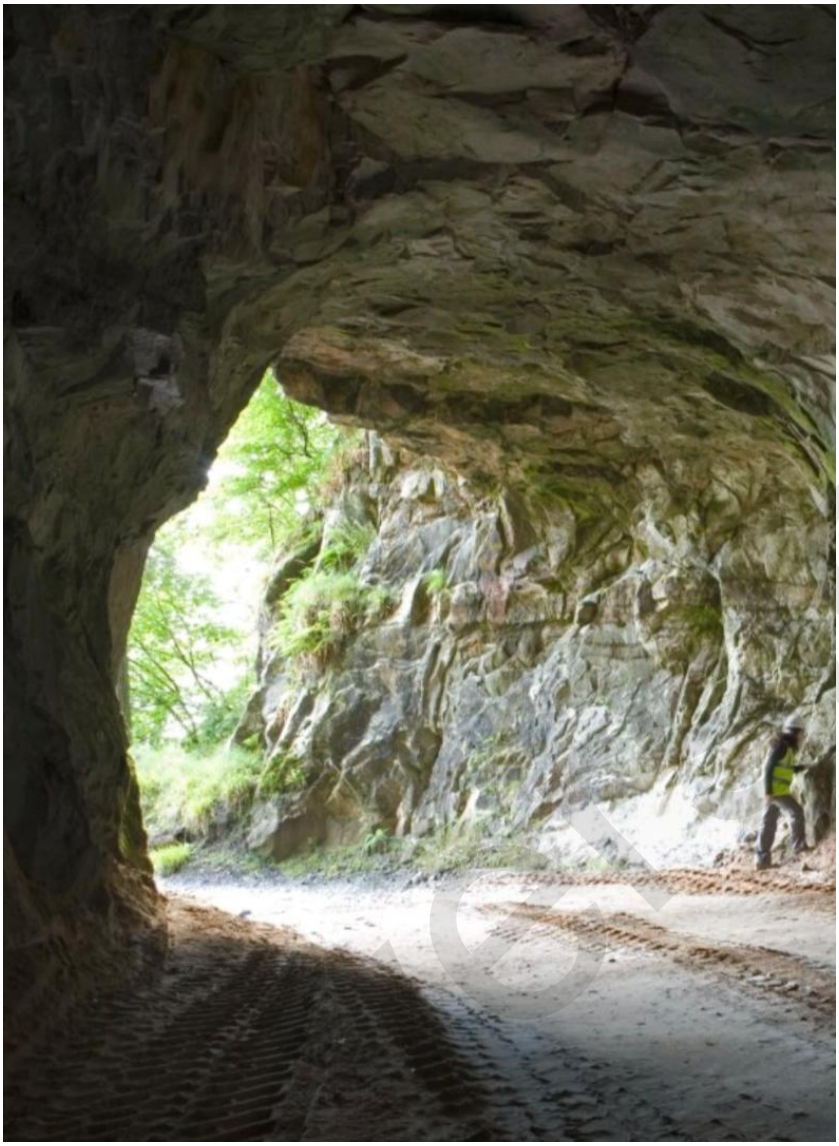


Figure 3-171: Exposure of Lochaline White Sandstone Formation strata at adit entrance. Person for scale.



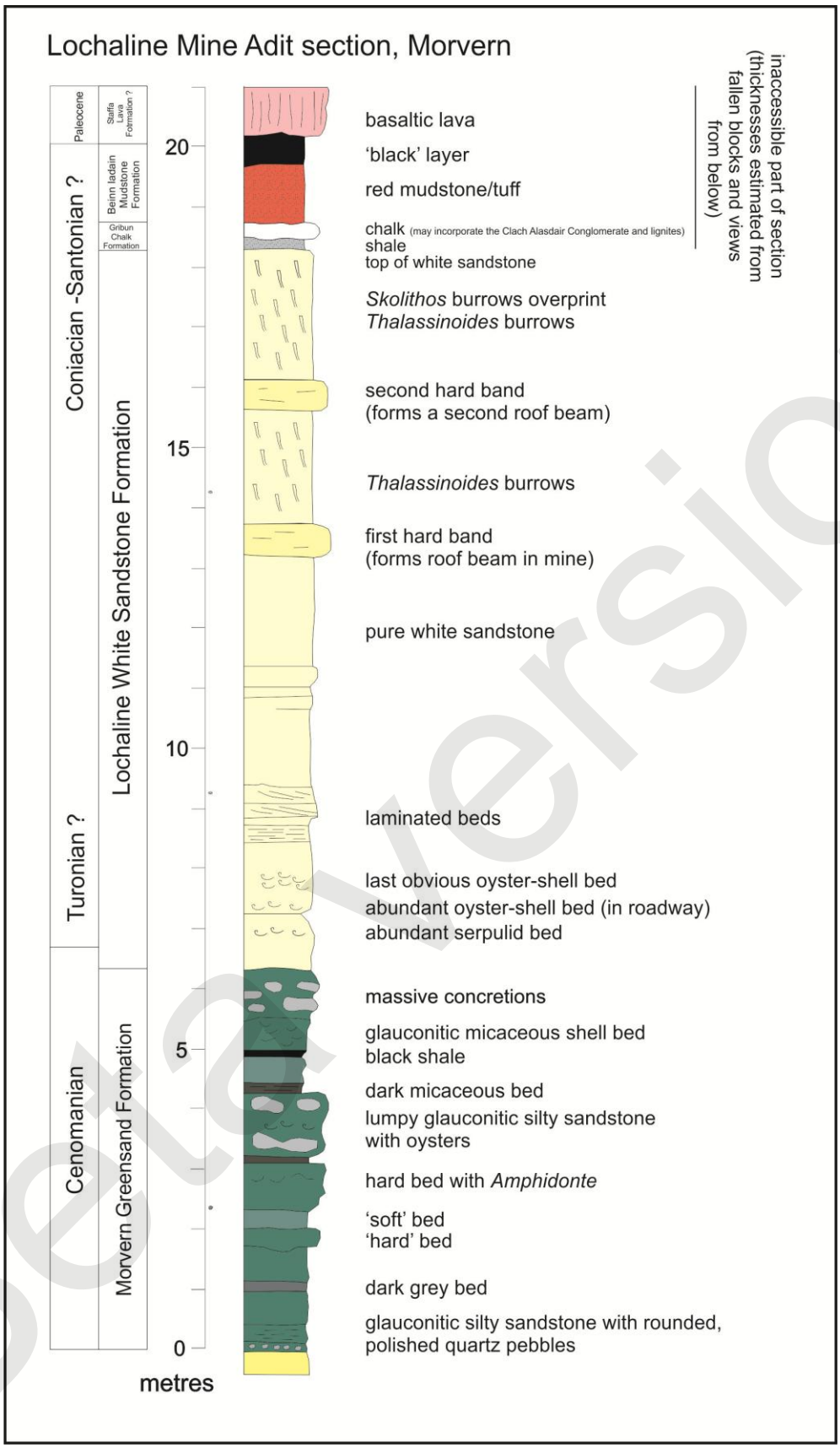
Figure 3-172: Exposure of Lochaline White Sandstone Formation within the mine.

Beta version



Figure 3-173: *Rhynchostrean* oyster shells, Morvern Greensand Formation, floor of the Lochaline mine adit. [Photograph courtesy of Rory Mortimore]

Beta version



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Figure 3-174: Composite stratigraphic log of the Upper Cretaceous section, Lochaline Mine, Morvern (after Mortimore & Long 2024).

The thickest Upper Cretaceous succession on Morvern crops out around the flanks of Beinn Iadain (Figure 3-153), where sandstones of the Morvern Greensand Formation are overlain sequentially by *ca*. 4 m of sandstones of the Lochaline White Sandstone Formation, *ca*. 1 m of silicified chalk, the Clach Alasdair Conglomerate with intraclasts of silicified chalk, and clastic sedimentary rocks with lignite of the Beinn Iadain Mudstone Formation (Figure 3-175; Figure 3-176; Figure 3-177).

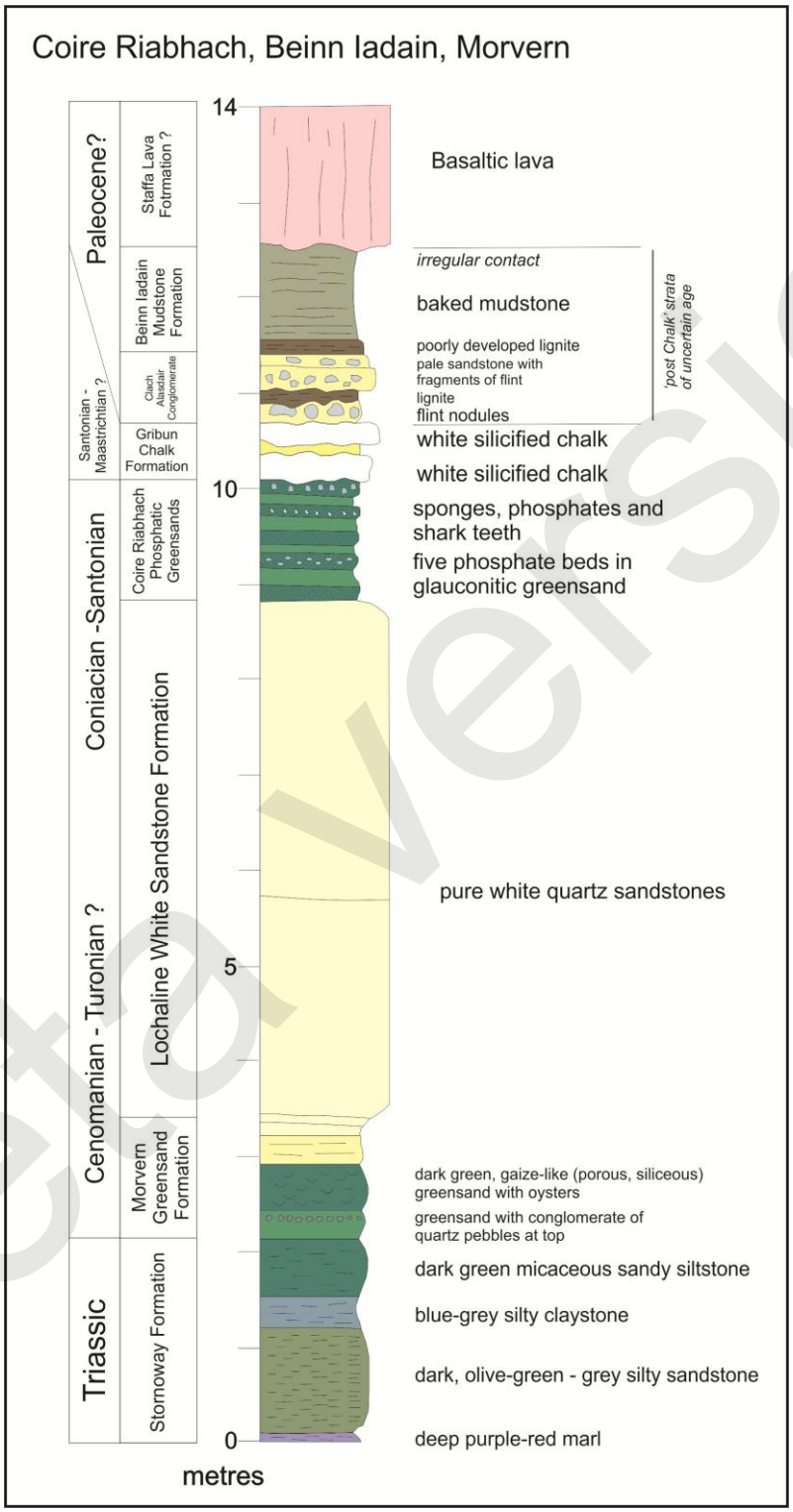


Figure 3-175: Stratigraphic log of the Upper Cretaceous section, Coire Riabhach, Beinn Iadain, Morvern (after Mortimore & Long 2024).

Beta version

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Figure 3-176: Prismatic-jointed Paleocene basaltic lavas unconformably overlying a thin sequence of 'post Chalk' sedimentary strata on the SE side of Beinn Iadain, Morvern. Person located at the sedimentary sequence and the unconformity.



Figure 3-177: Detail of the 'post Chalk' sedimentary sequence on the SE side of the Beinn Iadain ridge, Morvern. The section comprises (from base, upwards): brecciated chalk with flints (at hammer head), 2 cm black carbonaceous mudstone, 3 cm pale grey mudstone, 30 cm buff/grey sandstone, 1 cm carbonaceous mudstone (end of hammer shaft), 45 cm orange-weathering sandstone (directly above hammer), 10 cm laminated shale, 15 cm blocky shale, basaltic lava (top of view). Hammer *ca*. 30 cm long.

Browser version

3.6.8 Arran

Rocks of Cretaceous age on Arran are restricted to chalk with flints and white sandstone contained in several *remanié* masses within the Paleocene Central Arran Ring-complex, forming a depression known as 'Pigeon Cave' on Ard Bheinn (Figure 3-178; Figure 3-179) (Chapter 9). Microfossils and fragments of *Inoceramus* bivalves recovered from these rocks indicate a Late Cretaceous age (Tyrrell 1928). Most of the limestone is thermally altered but some pieces are merely indurated and resemble the chalk of Antrim.

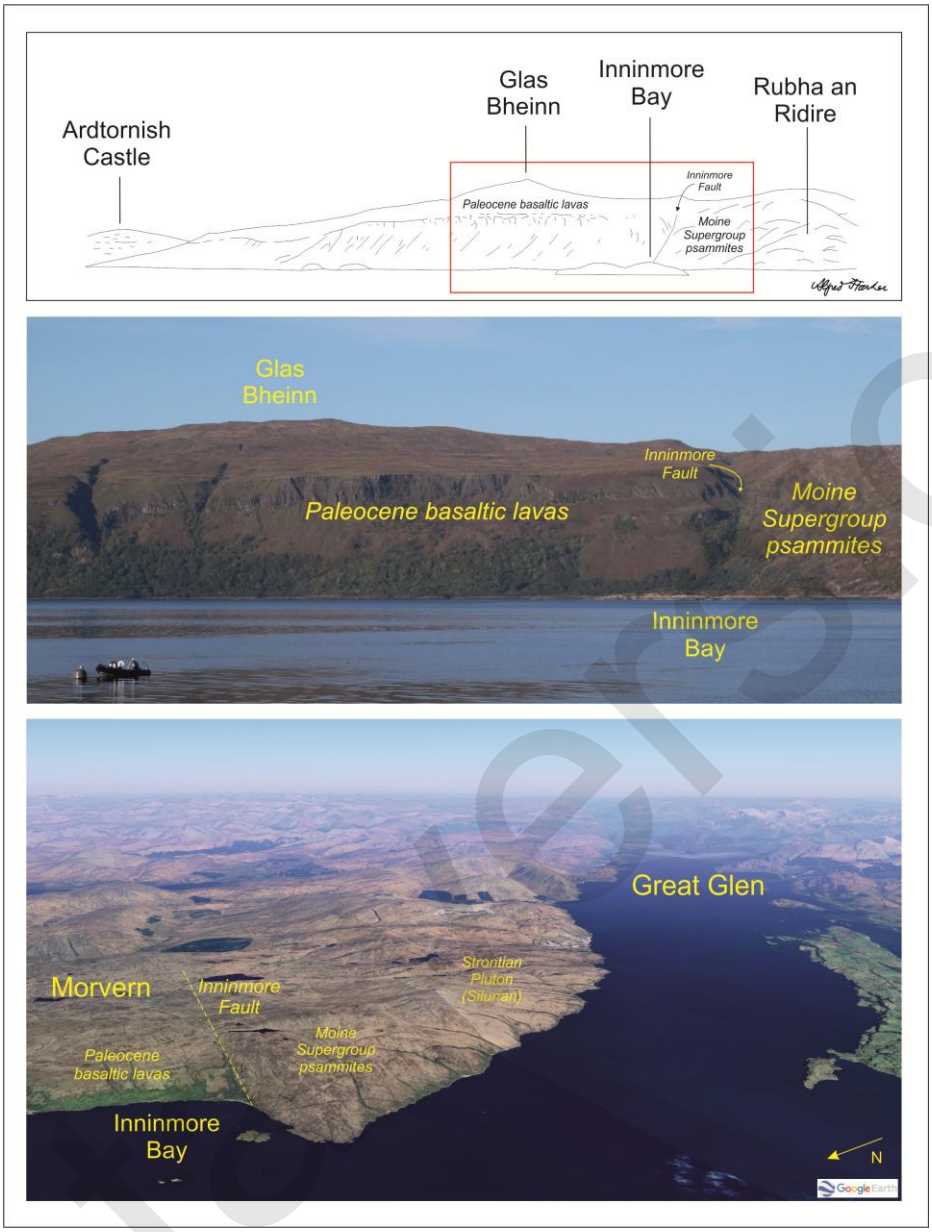


Figure 3-178: Pigeon Cave, Ard Bheinn, central Arran. [Photograph courtesy of Rory Mortimore]



Figure 3-179: Detail of Pigeon Cave, Ard Bheinn, central Arran. [Photograph courtesy of Rory Mortimore]

4 Pre-Paleocene Structure

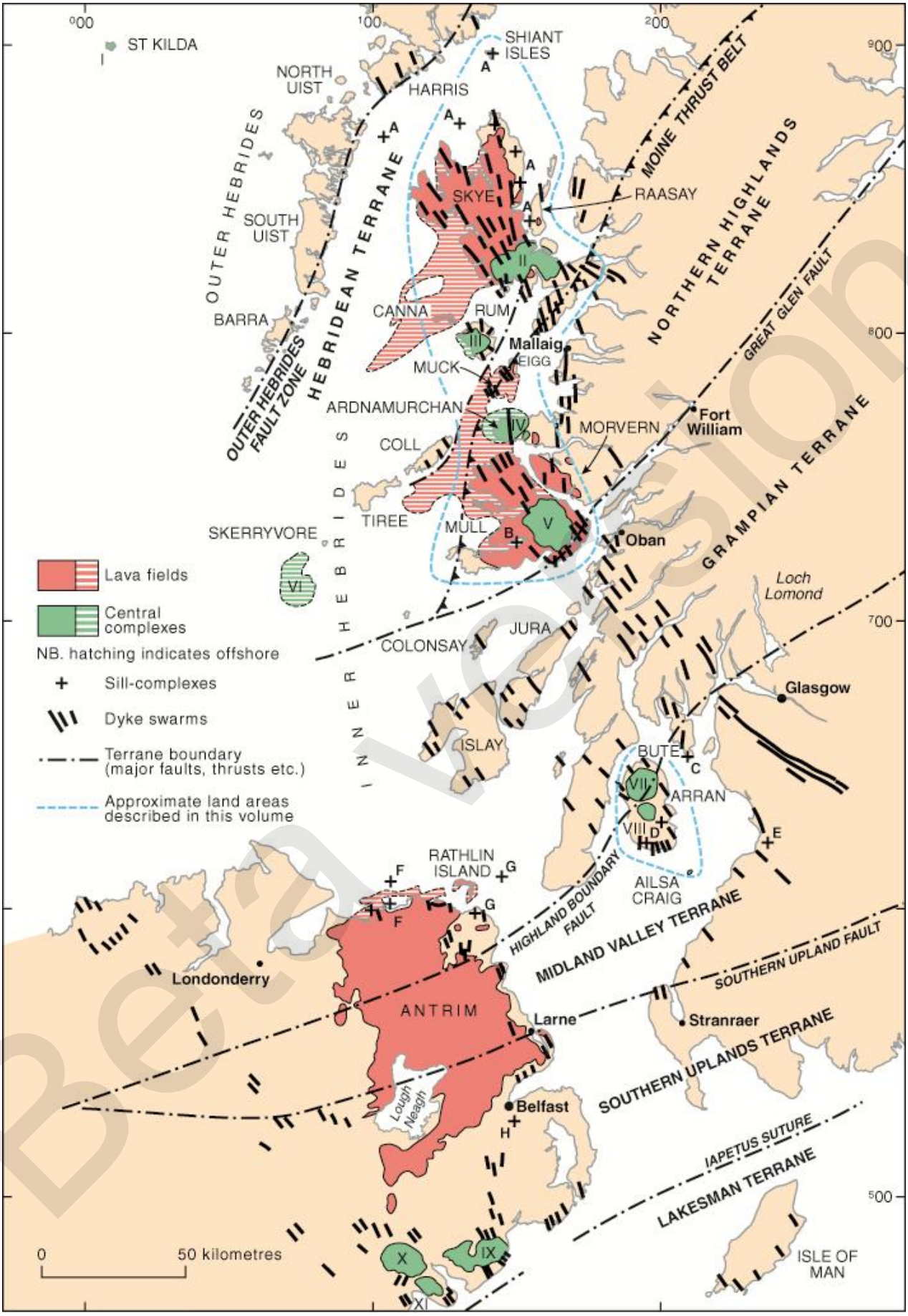


Basaltic lavas adjacent to the Inninmore Fault, Morvern

4.1 Introduction

The Archaean to Paleocene rocks that form the islands and seaboard of Western Scotland record a long and complicated geological history. The pre-Paleocene rocks and their structural relationships have influenced the Paleocene tectonic and magmatic events, both extrusive and intrusive, to a significant extent. Two pre-Paleocene structural elements dominate the area: first, the thrust belt that formed during the Early Palaeozoic Caledonian Orogeny, the Moine Thrust Zone (MTZ), which defines the main terrane boundaries; second, the N-S -trending sedimentary basins (or troughs) filled with Late Palaeozoic and Mesozoic sedimentary rocks, together with the intervening ridges that are largely made of Precambrian rocks. It is therefore convenient to consider the pre-Paleocene structure of the district in two parts: events prior to the Late Palaeozoic, and from the Late Palaeozoic to the end of the Mesozoic Era (Figure 4-1; Figure 4-2).

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Figure 4-1: Simplified geological map showing the positions of Paleocene central complexes, lava fields, sill-complexes and dyke swarms in western Scotland and NE Ireland (after Emeleus & Bell 2005).

Central complexes: *I*, St Kilda; *II*, Skye; *III*, Rum; *IV*, Ardnamurchan; *V*, Mull; *VI*, Blackstones Bank (submerged); *VII*, Arran Northern Granite Pluton; *VIII*, Arran Central Ring Complex; *IX*, Mourne Mountains; *X*, Slieve Gullion; *XI*, Carlingford.

Sill-complexes: *A*, Little Minch; *B*, Loch Scridain; *C*, Bute; *D*, South Arran; *E*, Prestwick-Mauchline; *F*, Portrush; *G*, Fair Head; *H*, Scarbo.

Dyke swarms: short, thick bars show trends of the dyke swarms.

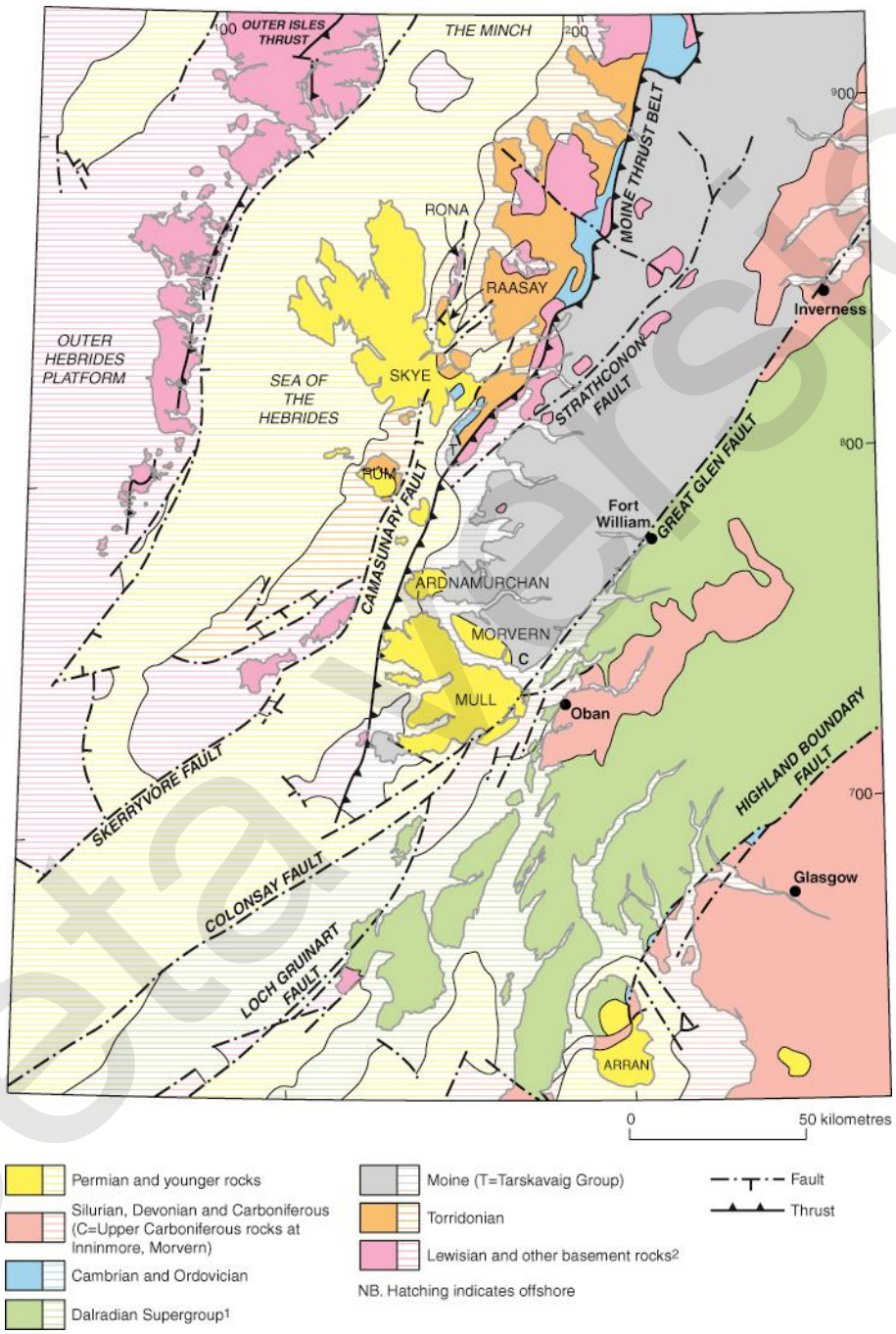


Figure 4-2: Onshore and offshore distribution of Precambrian and Lower Palaeozoic rocks along the western seaboard of Scotland [1, includes the Bowmore and Colonsay groups on and offshore Islay; 2, includes gneisses of the Rhinns Complex south of the Great Glen Fault] (after Emeleus & Bell 2005).

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4.2 Early Palaeozoic and older structures

The deformation events associated with the Caledonian Orogeny were responsible for several notable features in the district. On Skye, the MTZ separates rocks of the foreland Hebridean Terrane (Lewisian Gneiss Complex, Torridonian Supergroup and Cambro-Ordovician sedimentary rocks) from rocks of the Moine Supergroup forming the Northern Highlands Terrane to the east.

On Skye, south of Broadford in Strath, movements on the Ben Suardal Thrust Plane transported Torridonian Supergroup sandstones over Ordovician limestones and dolostones at Beinn Suardal (Bheinn Shuardail). The Moine Thrust crops out as far south as the Point of Sleat, Skye, although farther south it is either concealed beneath Mesozoic strata of the Inner Hebrides Basin or has been removed by erosion.

The status of any fault (or faults) separating Iona (consisting of the Lewisian Gneiss Complex overlain by Iona Group strata (possibly Torridonian Supergroup)) and the Ross of Mull (consisting of the Palaeozoic Ross of Mull Pluton intruded into Moine Supergroup psammites, pelites and garnet amphibolites) has been debated; one possibility is it is the location of the MTZ. However, detailed structural analysis of the gneisses on Iona suggests that the structure within the Sound of Iona is a steep normal fault with a downthrow to the ESE (Figure 4-3) (Potts *et al.* 1995).

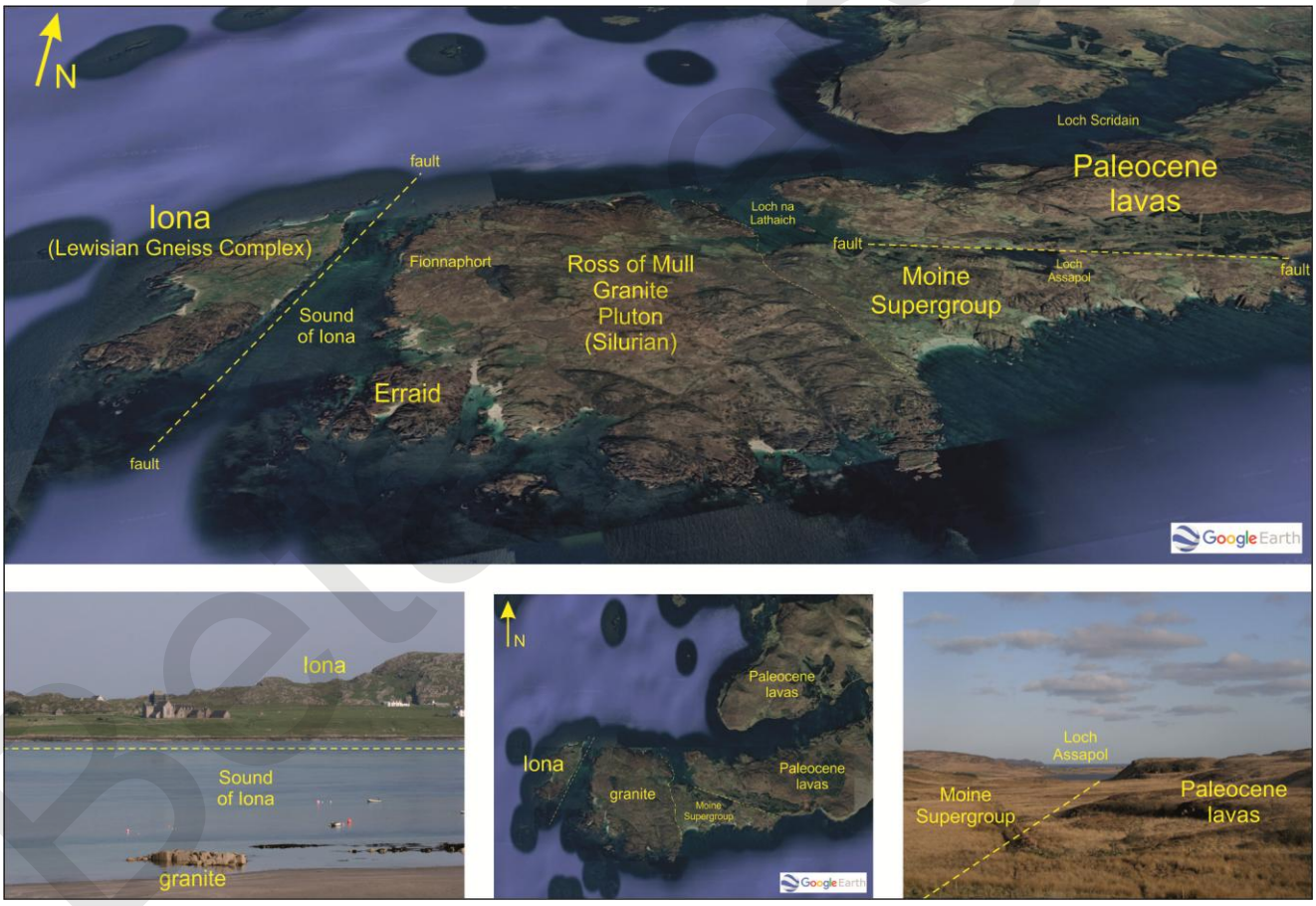


Figure 4-3: Annotated oblique Google Earth© images and field photographs illustrating relationships of main structural elements in the SW Mull – Iona area.

Revision

To the south, the Great Glen Fault and the Highland Boundary Fault (Figure 4-4), which form two of the major terrane boundaries in Scotland, were active during the Palaeozoic; the Great Glen Fault was subsequently subjected to further significant post-Paleocene movement(s), indicated by displacements of Paleocene dykes (Chapter 7).

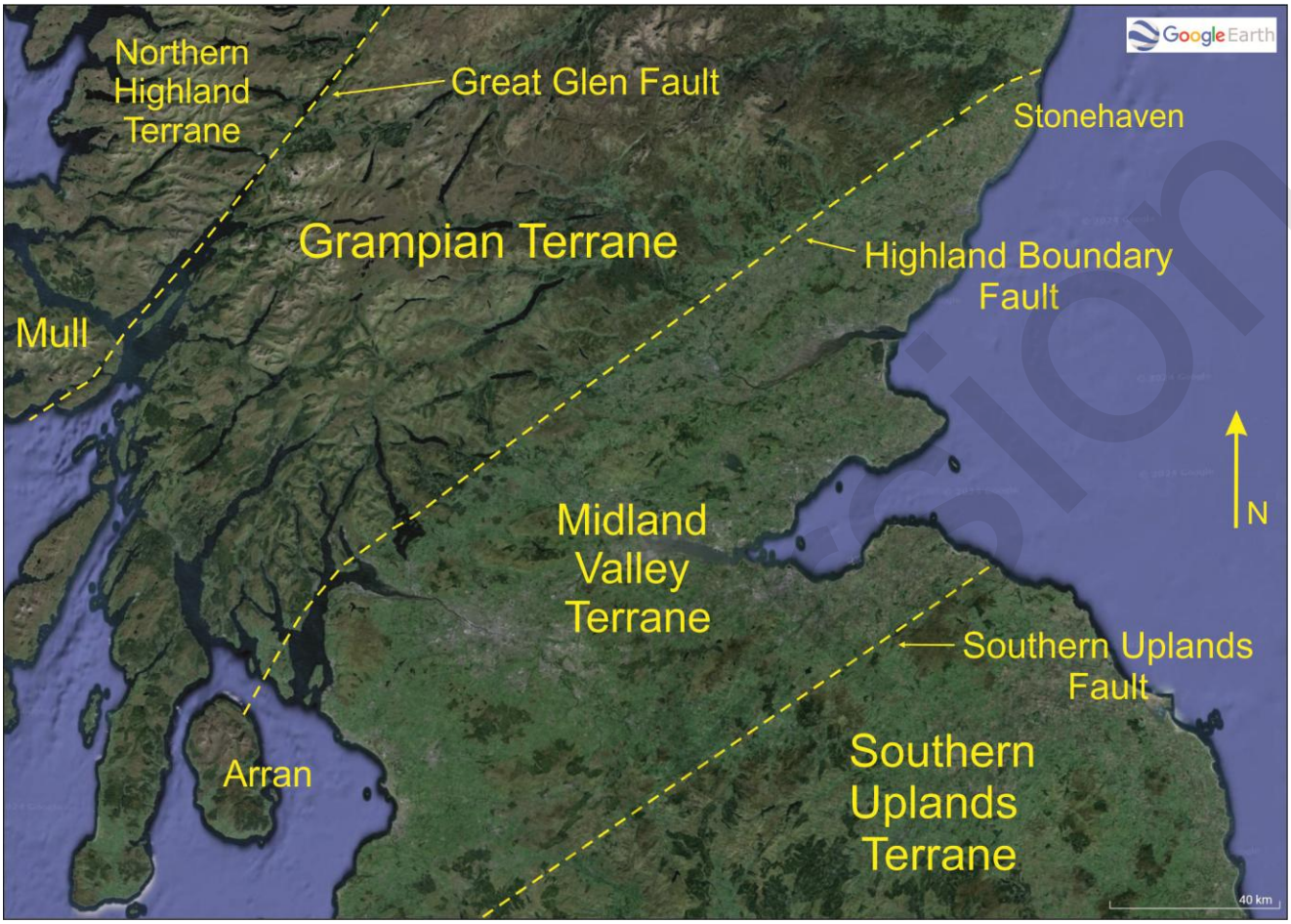


Figure 4-4: Annotated Google Earth© image illustrating the boundaries of the terranes in southern Scotland.

On Mull, the Great Glen Fault is readily defined between Craignure and NW of Loch Spelve, where Moine Supergroup strata crop out, and Loch Don, where phyllites and limestones of the Appin Group of the Dalradian Supergroup occur. Furthermore, the breccias of the Mull Central Complex (Chapter 9) provide additional proof of this fault in eastern Mull: Moine clasts are common in the breccias, whereas there are none of Dalradian lithologies. South of Loch Don, the fault changes trend from its NE strike to a SE strike along Loch Spelve and Loch Buie, where it has been deflected by the Mull Central Complex.

The Highland Boundary Fault and the associated Highland Border Complex cross Scotland from Stonehaven in the NE to Bute in the SW. In north Arran, where Dalradian Supergroup strata rocks crop out extensively, the pillow lavas, cherts and mudstones in North Glen Sannox are assigned to the Highland Border Complex (Figure 4-5). Various faults in NE Arran have been proposed as continuations of the Highland Boundary Fault, for example the Corloch Fault and the fault at the eastern edge of the North Arran Granite Pluton, exposed in the White Water above Corrie.

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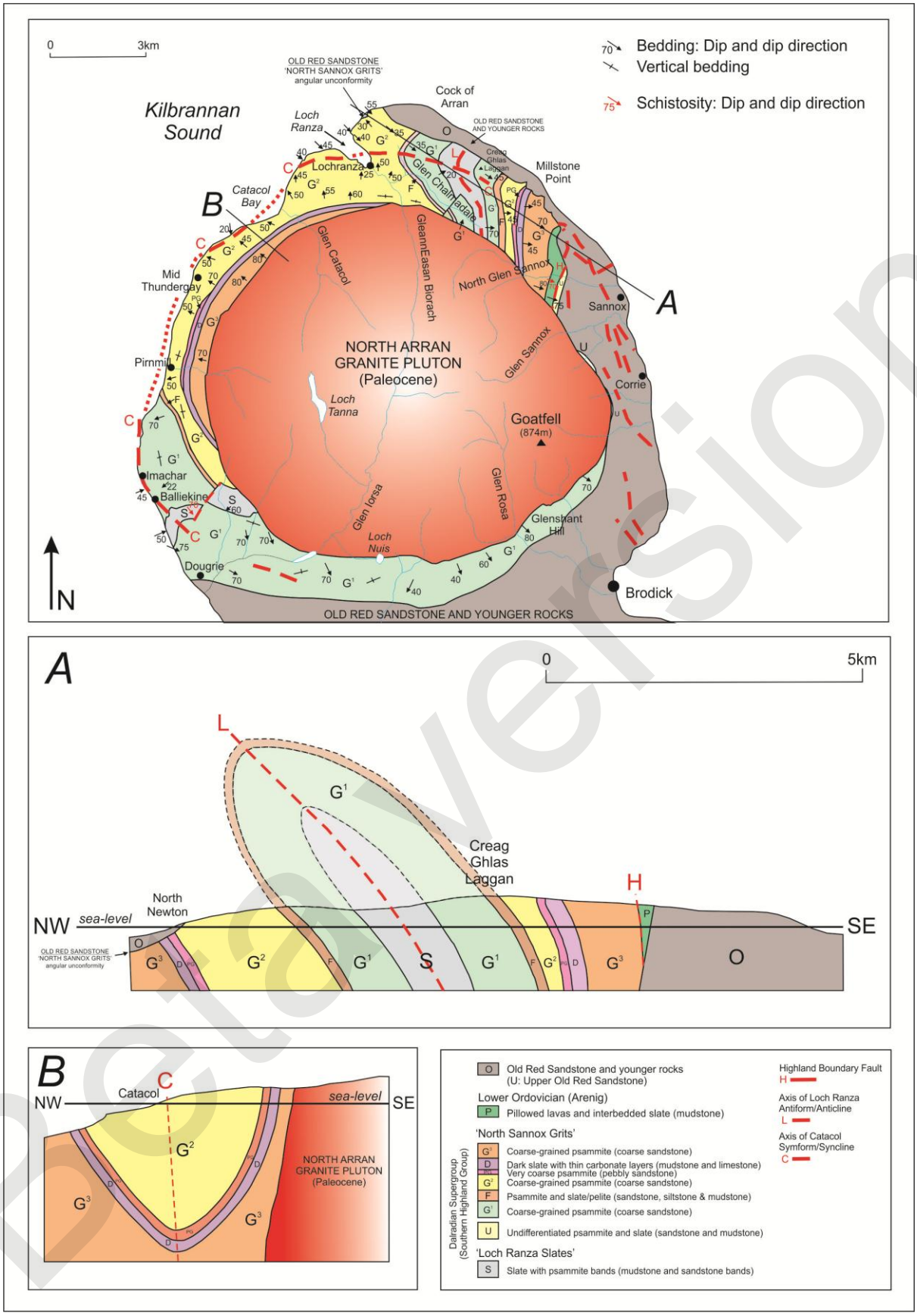


Figure 4-5: Simplified geological map and cross-sections of north Arran, illustrating the distribution of the main lithologies and structures, including the Highland Boundary Fault (after various sources).

On the south side of the granite, the contact between Dalradian rocks and Devonian (Old Red Sandstone) sandstones and conglomerates was also once regarded as the continuation of the Highland Boundary

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Fault, deflected during the forcible emplacement of the granite pluton (Tyrrell 1928). Subsequently, however, the Devonian strata have been shown to lie unconformably on the Dalradian rocks south of the granite (Friend *et al*. 1963) and so movement on these faults appears to have been at least in part contemporaneous with granite emplacement (England 1992). Remnants of the Highland Boundary Fault are present in the North Glen Sannox area, but the course of the fault to the SW is unclear.

4.3 Late Palaeozoic to Mesozoic Structures

The Sea of the Hebrides and Inner Hebrides basins (or troughs) are amongst the most striking pre-Paleocene structures in the district (Figure 4-6).

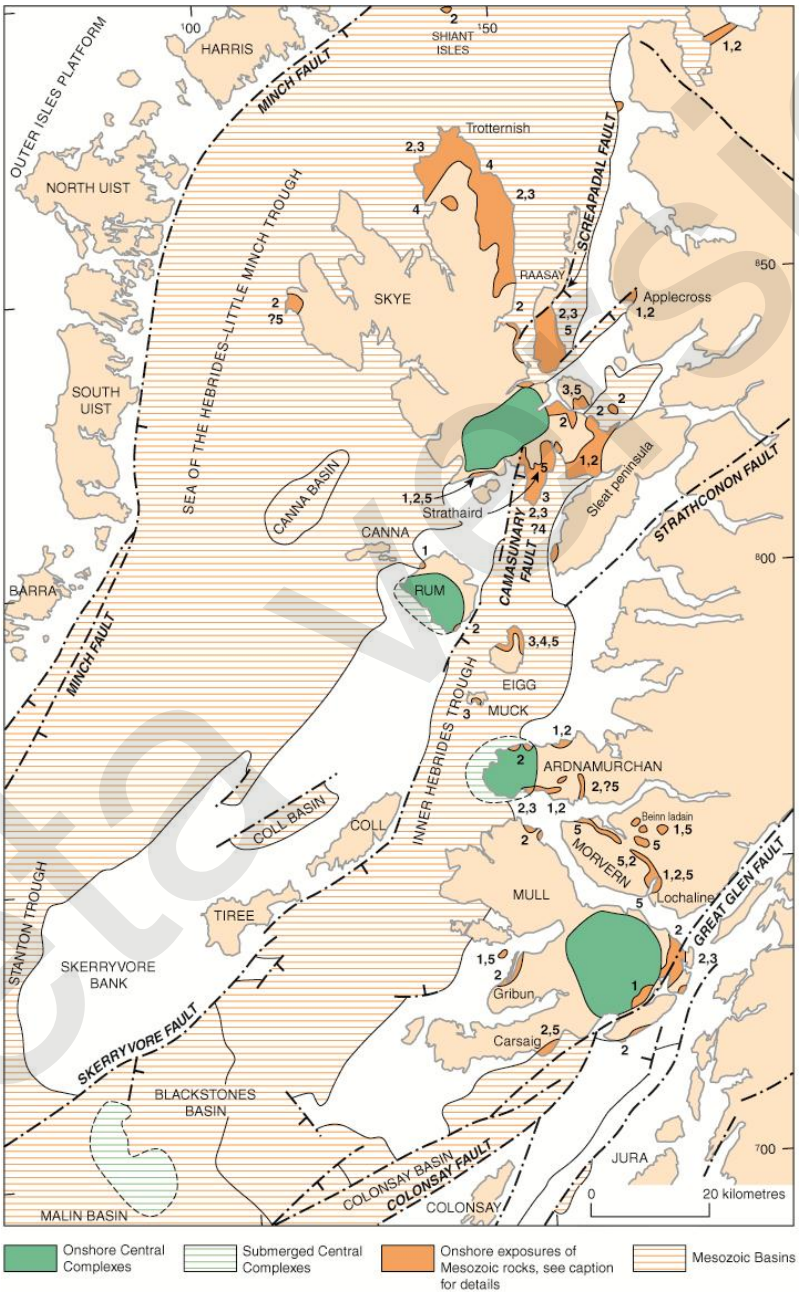


Figure 4-6: Simplified geological map of the Inner Hebrides showing the location of Mesozoic basins, the location where Mesozoic rocks occur onshore, and the locations of the Paleocene central complexes. Pre-Mesozoic rocks are uncoloured (after Fyfe *et al*. 1993).

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On Skye, there is unequivocal evidence that the main movement on the Camasunary–Skerryvore Fault, which forms part of the western boundary of the Inner Hebrides Basin, occurred prior to the eruption of the Paleocene lavas. At Camasunary Bay, Middle Jurassic rocks are downfaulted by as much as 200 m against Lower Jurassic and Torridonian strata to the west, but there is only minor displacement of the Paleocene lavas that overlie both (Figure 4-7).

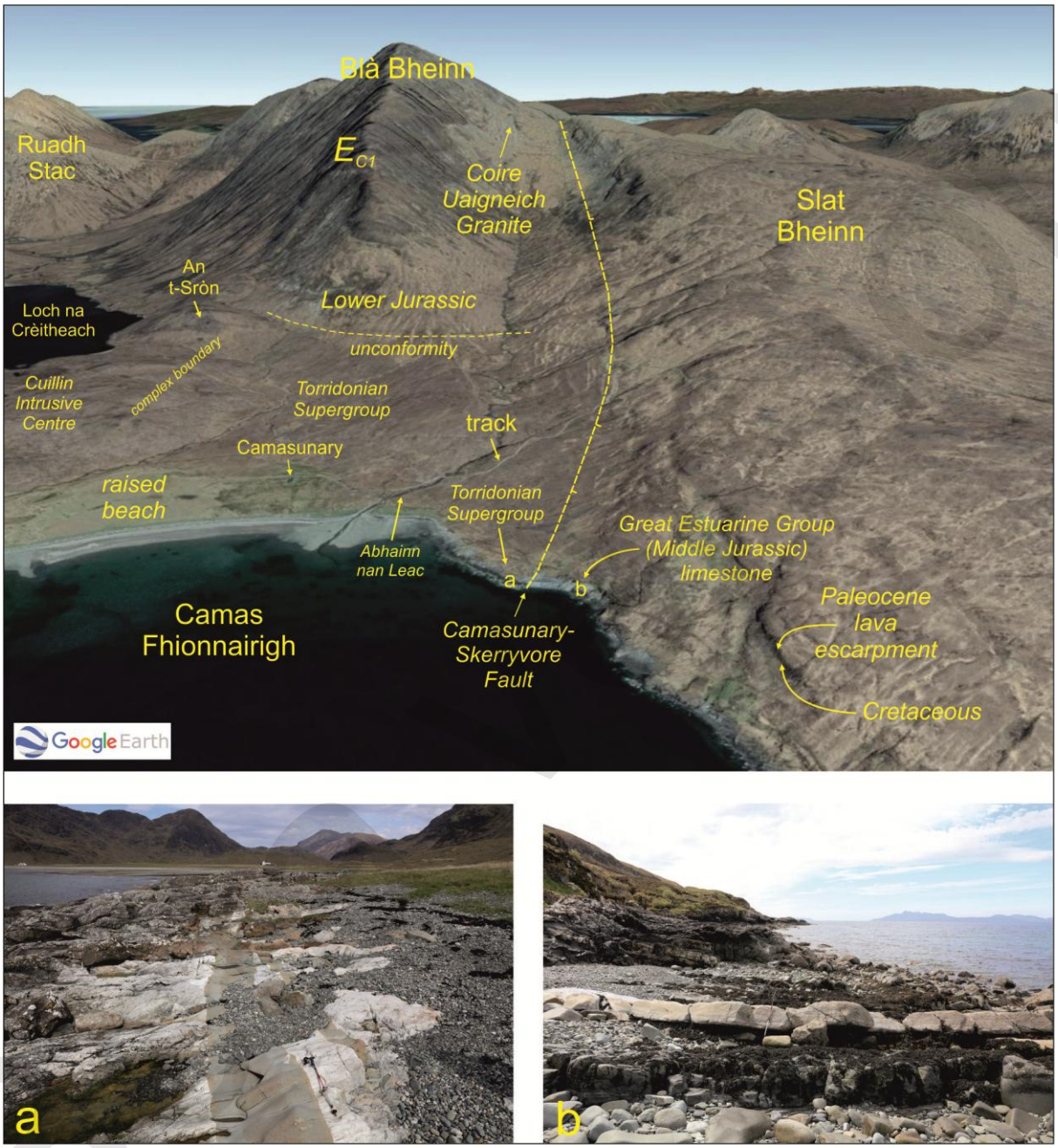


Figure 4-7: Annotated oblique Google Earth© image and field photographs illustrating the relationships of main structural elements in the Camasunary Bay area, south-central Skye: (a) Paleocene dyke intruded into Torridonian Supergroup strata on west side of the Camasunary-Skerryvore Fault; and, (b) Great Estuarine Group strata on the east side of the fault.

To the south, the thin Lower Jurassic sequence on Rum is separated from the thick Middle Jurassic sequence of Eigg by the southern continuation of the Camasunary–Skerryvore Fault. Farther south, the proven movements on this fault post-date the Paleocene lavas.

On Skye, the northern continuation of the Camasunary–Skerryvore Fault is disturbed and largely obscured by the central complex, which may have caused a westerly offset of the fault. Splays of the fault may continue on Raasay as the Screapadal Fault (Figure 4-8) and as a major fault in SE Scalpay.

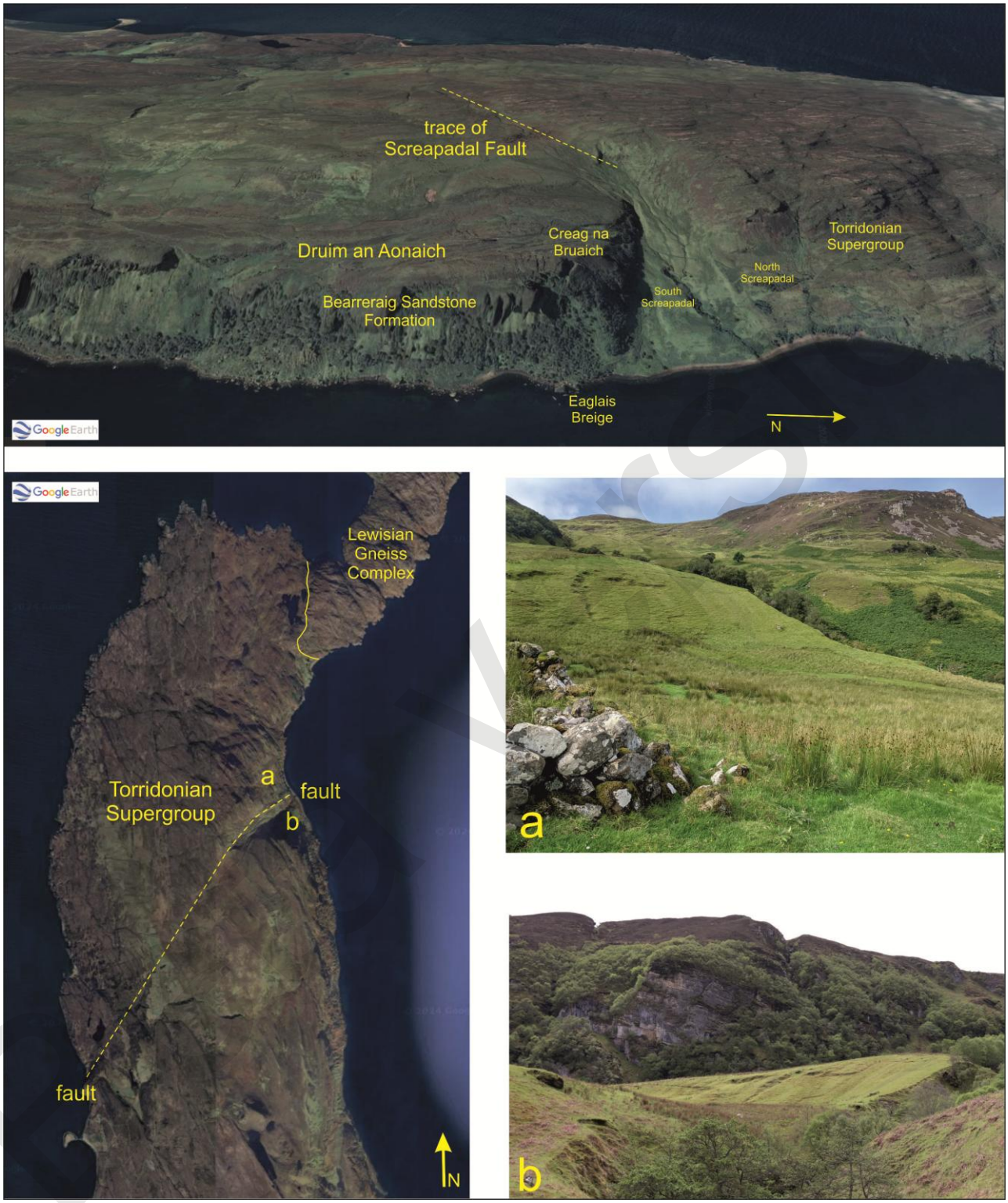


Figure 4-8: Annotated oblique Google Earth© images and field photographs illustrating the main features of the Screapadal Fault in central Raasay: (a) Torridonian Supergroup strata on the north side of the fault; and, (b) Lower and Middle Jurassic strata on the south of the fault.

On Rum, the general moderate WNW to NW dip of the Torridonian and Triassic strata pre-dates the emplacement of the Paleocene central complex. A major fault displacing Torridonian strata on

Bloodstone Hill predates the Paleocene lavas and intrusions. Also on Rum, it is likely that the major N-S -trending Long Loch Fault had considerable pre-Paleocene movement (Figure 4-9).

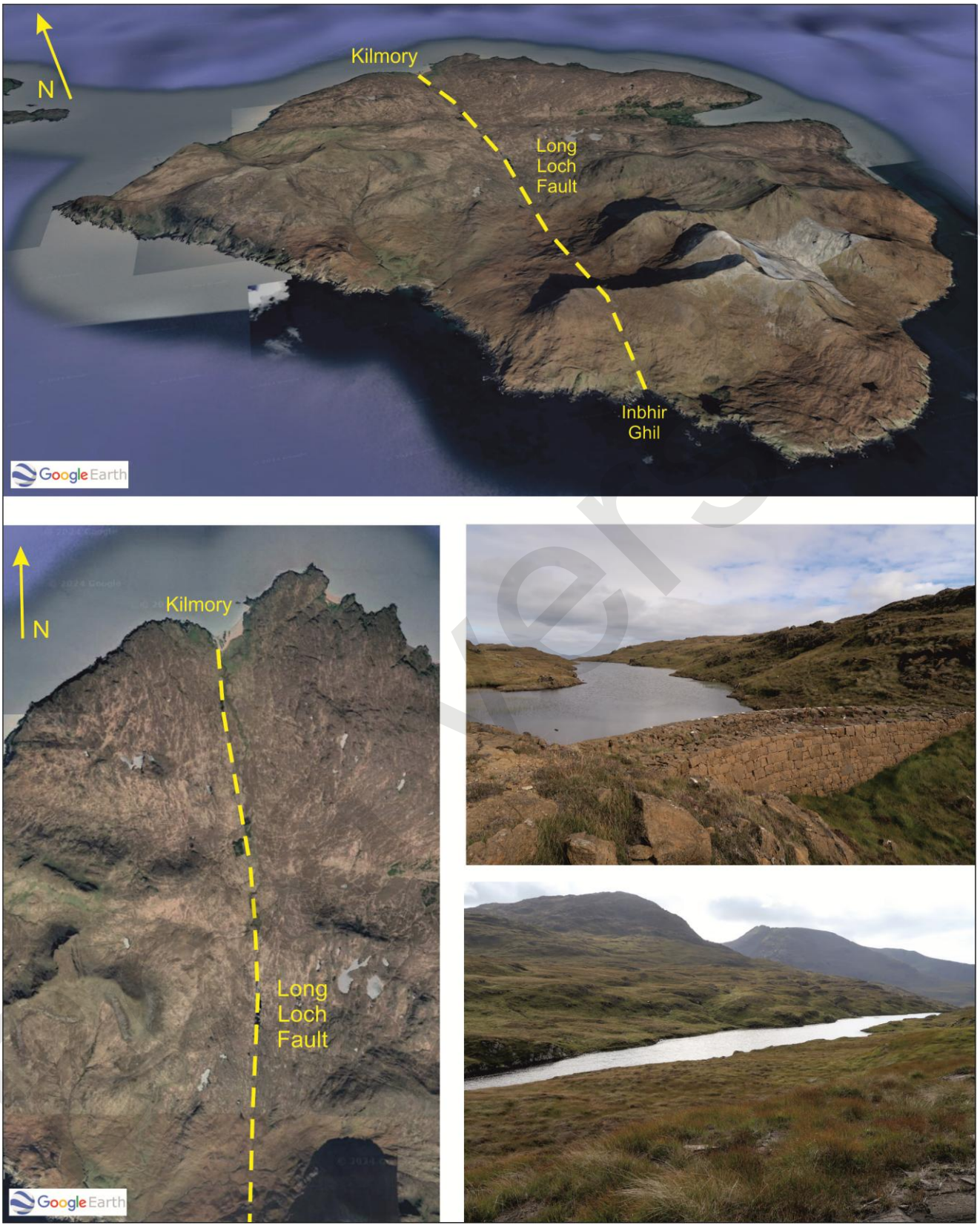


Figure 4-9: Annotated Google Earth© images and field photographs illustrating the Long Loch Fault on Rum.

On Eigg, movement on the normal Laig Gorge Fault affects the Mesozoic rocks in the opposite sense to that found in the overlying Paleocene basaltic lavas (Figure 4-10).

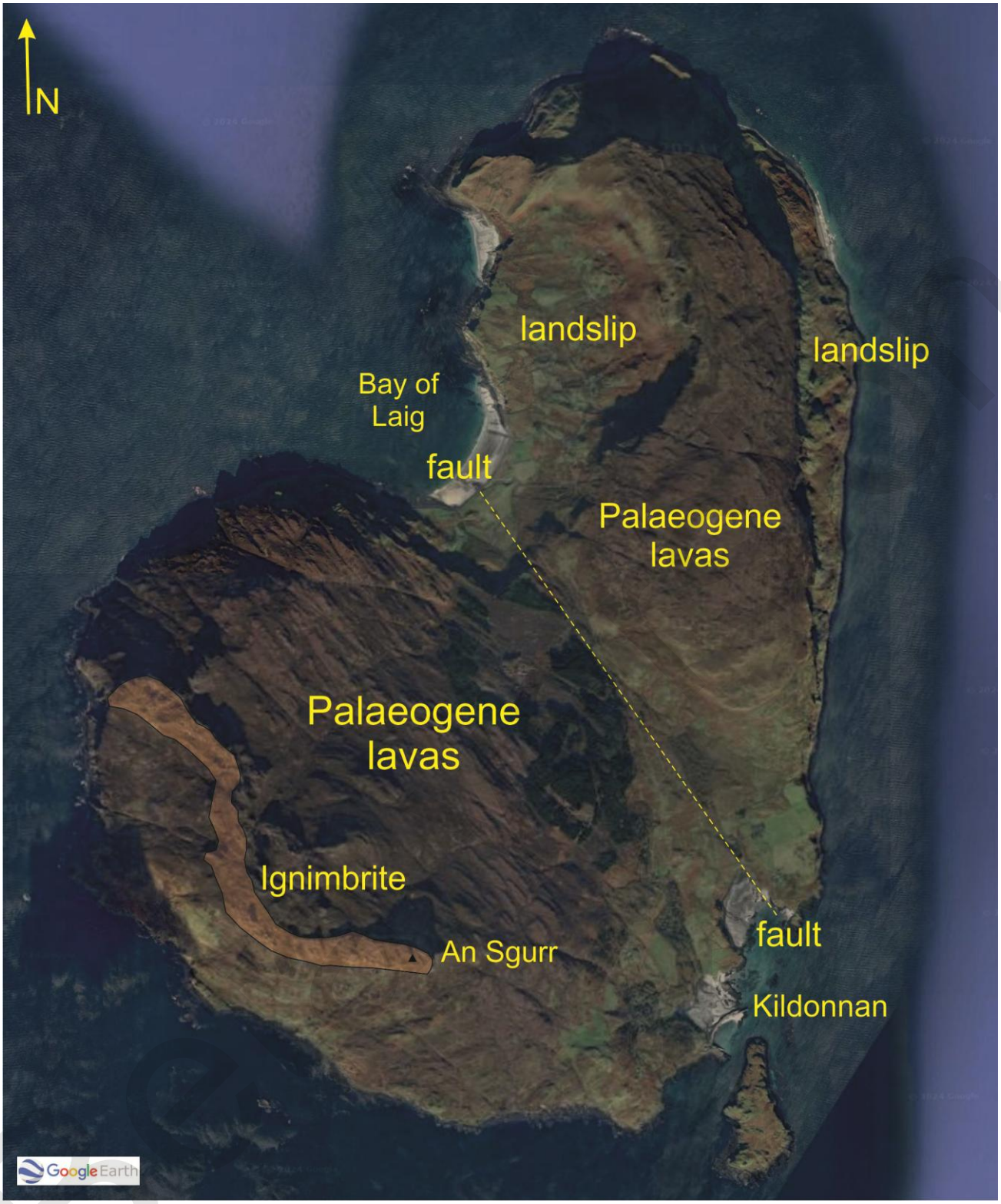


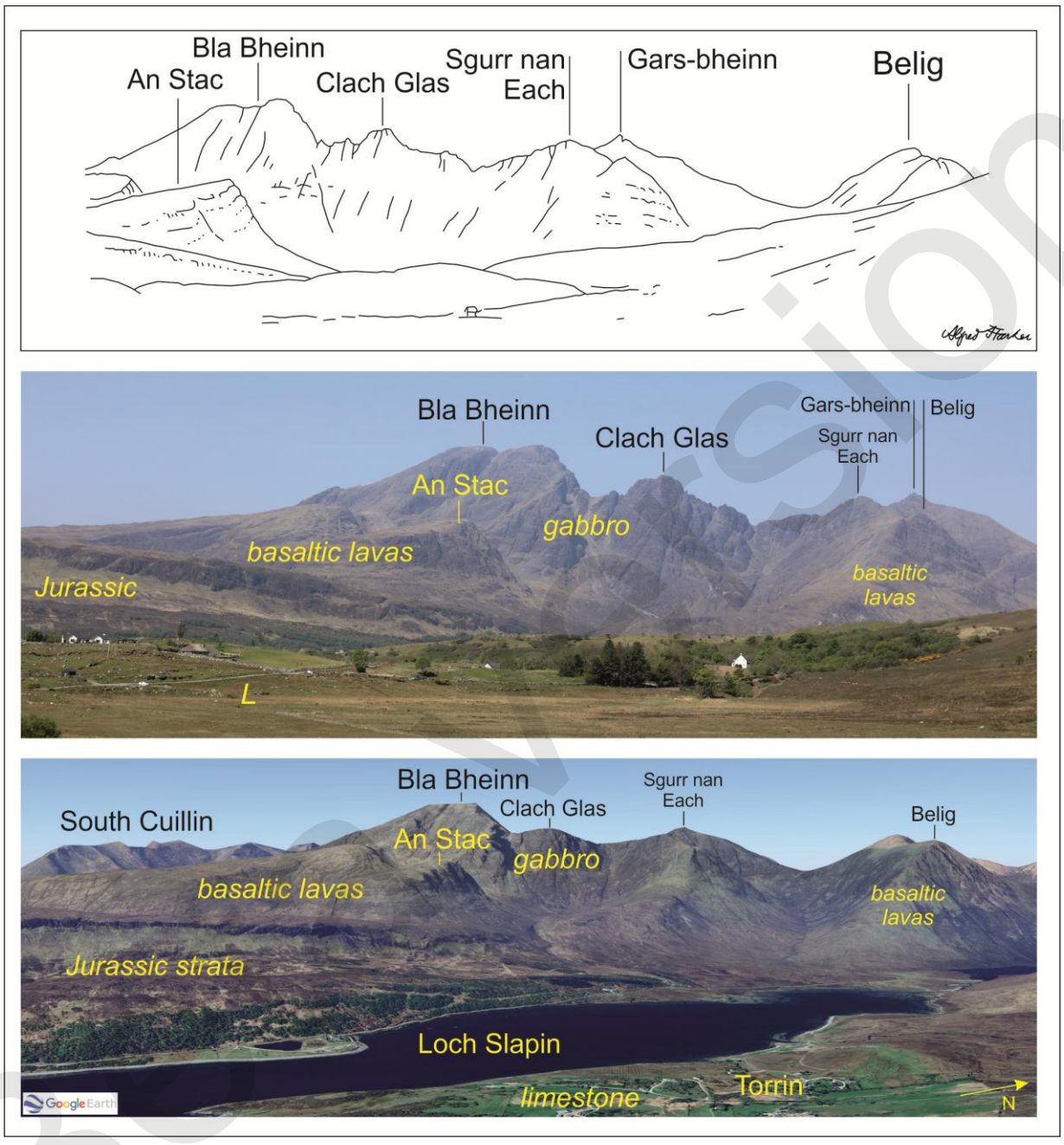
Figure 4-10: Annotated Google Earth© image illustrating the location of the Laig Gorge Fault.

Throughout the district there is evidence of a period of uplift prior to deposition of the Upper Cretaceous strata. Small, scattered outcrops of these rocks overlie a wide variety of older rocks that range in age from Proterozoic to Jurassic. Furthermore, there is widespread evidence that uplift and denudation at the close of the Cretaceous Period, or very early in the Paleocene, gave rise to an undulating land surface that may have had significant local relief. Hence, the earliest Paleocene lavas and the associated sedimentary strata rest on a variety of older rocks and some of the oldest Paleocene clastic sediments were clearly derived by vigorous contemporaneous erosion. Furthermore, the field relationships of the volcanic

sequence on Skye and the Rum and Skye central complexes indicate that there were significant time differences between the emplacement of the central complexes: first the Rum Central Complex, then the Skye Lava Field, then the Skye Central Complex (Chapters 6 and 9). The drainage systems that developed as a consequence of the growth of each of the volcanoes, atop their respective central complex, will have contributed significantly to the architecture of the syn-volcanic sedimentary rocks, mainly debris flow, fluvial and lacustrine deposits.

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5 Paleocene Igneous Geology: Regional Setting



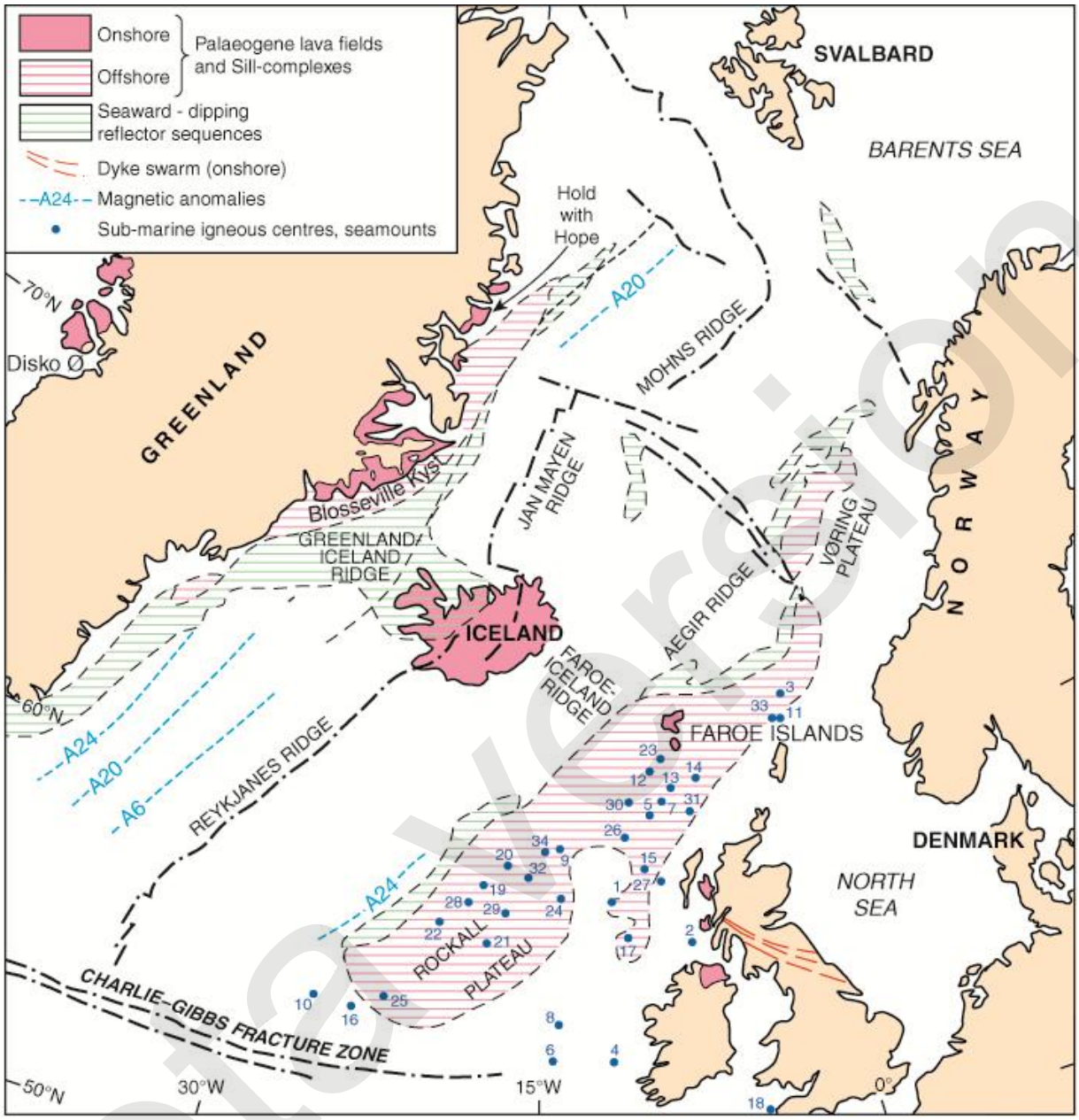
Basaltic lavas intruded by the Cuillin Intrusive Centre, Skye

5.1 Introduction

The Paleocene rocks that comprise the central complexes, subaerial lava fields, linear dyke swarms and sill-complexes of the Hebridean Igneous Province (HIP) are part of the much larger, North Atlantic Igneous Superprovince (NAIS) (Figure 5-1). This magmatism was the result of decompressional melting as the proto-Icelandic mantle plume impacted on the base of the continental lithosphere towards the end of the Cretaceous Period. Lithosphere thinning, most likely dating from the Mesozoic Era when significant rift

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basins formed along the western seaboard of Scotland, enabled batches of magma to rise towards the Earth's surface (Thompson & Gibson 1990).



1 Anton Dohrn
2 Blackstones
3 Brendan (Shetland)
4 Brendan (Ireland)
5 Darwin
6 Donn
7 Drekaegya
8 Drol
9 East George Bligh
10 Eriador
11 Erlend
12 Faroe Bank
13 Faroe Bank Channel Knoll
14 Fraenir
15 Geikie
16 Gondor
17 Hebrides Terrace
18 Lundy
19 Lyonesse
20 Mammal
21 Mentone
22 Owlsgard
23 Regin Smidur
24 Rockall
25 Rohan
26 Rosemary Bank
27 St Kilda
28 Sandarro
29 Sandastre
30 Sigmundur
31 Sula Sgeir
32 Swithin
33 West Erlend
34 West George Bligh

Figure 5-1: The North Atlantic Igneous Superprovince (NAIP), showing the extent of onshore and offshore igneous activity (after Emeleus & Bell 2005).

Erosion since *ca.* 55 Ma has removed the upper parts of the lava fields and revealed the hearths of the main volcanoes: the central complexes (Figure 5-2). Magmatism continues today on Iceland and along the Mid-Atlantic Ridge, but represents a much smaller, less productive stage in the evolution of the plume.

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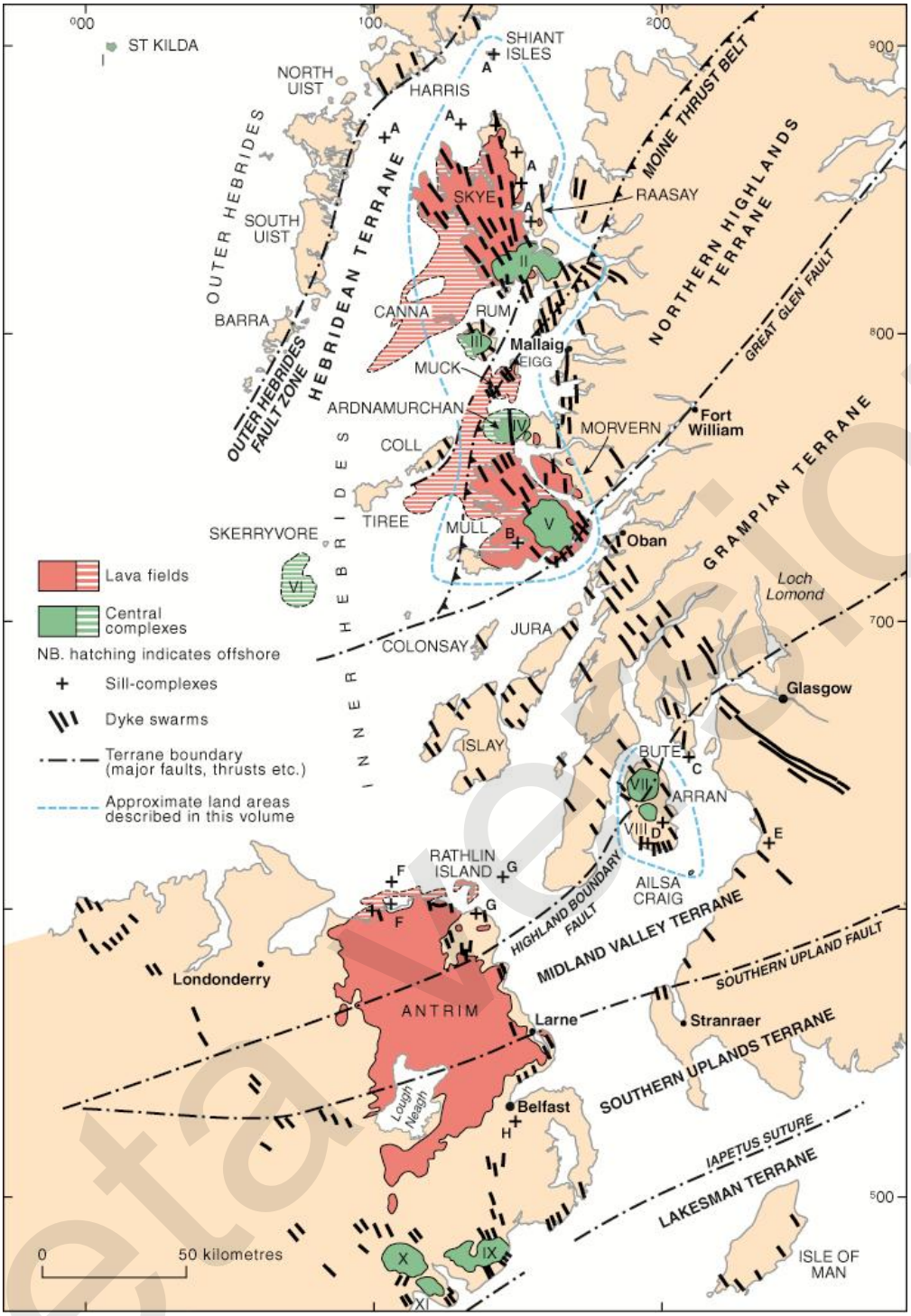


Figure 5-2: Simplified geological map showing the positions of Paleocene central complexes, lava fields, sill-complexes and dyke swarms in western Scotland and NE Ireland (after Emeleus & Bell 2005).

Central complexes: *I*, St Kilda; *II*, Skye; *III*, Rum; *IV*, Ardnamurchan; *V*, Mull; *VI*, Blackstones Bank (submerged); *VII*, Arran Northern Granite Pluton; *VIII*, Arran Central Ring Complex; *IX*, Mourne Mountains; *X*, Slieve Gullion; *XI*, Carlingford.

Sill-complexes: *A*, Little Minch; *B*, Loch Scridain; *C*, Bute; *D*, South Arran; *E*, Prestwick-Mauchline; *F*, Portrush; *G*, Fair Head; *H*, Scarbo.

Dyke swarms: short, thick bars show trends of the dyke swarms.

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5.2 General Observations

The British sector of the NAIS has been referred to variously as the British Paleocene/Paleocene/Tertiary Igneous/Volcanic Province, with most of the Scottish part cropping out across the Inner Hebrides and adjacent Scottish Mainland, giving rise to, for example, the spectacular scenery of islands such as Skye, Rum and Mull (Chapter 1). Here, it is referred to as the Hebridean Igneous Province (HIP). The remainder is situated in the Firth of Clyde and crosses the Southern Uplands into NE England.

Magma ascended through the lithosphere, predominantly along vertical NW-SE -trending fissures represented today by the major linear dyke swarms (Chapter 7), such as on Skye and Mull. The central complexes are located where the intensity of the dyke swarms is greatest and the degree of crustal dilation (SW-NE) greatest, possibly influenced by older crustal structures (Chapter 4). Recognized candidate structures include the Highland Boundary Fault, the Great Glen Fault, and other younger basin-bounding faults, such as the Camasunary-Skerryvore Fault, that developed during the formation of the underlying Mesozoic basins.

Seismic reflection and refraction studies have revealed that the NE Atlantic Ocean between NW Europe and Greenland comprises thick sequences (up to 6,000 m) of seaward-dipping reflectors. These are attributed to extrusive igneous rocks, erupted at the time of rifting and the initiation of ocean floor spreading (White 1988). Much of the volcanic activity occurred above sea level because of the dynamic support provided by the plume (White & Mackenzie 1989). This is demonstrated by the presence of inter-lava palaeosols recovered from deep-sea boreholes (e.g. Viereck *et al.* 1988; Millett *et al.* 2021). In addition, large amounts of igneous rock, up to 1,500 m thick, were underplated during the initial stages of rifting. The landward equivalents of the offshore lavas include the thick and laterally continuous flood basalt lavas of west and east Greenland, and the less extensive lava fields of the Faroe Islands, NW Scotland and NE Ireland (Figure 5-3).

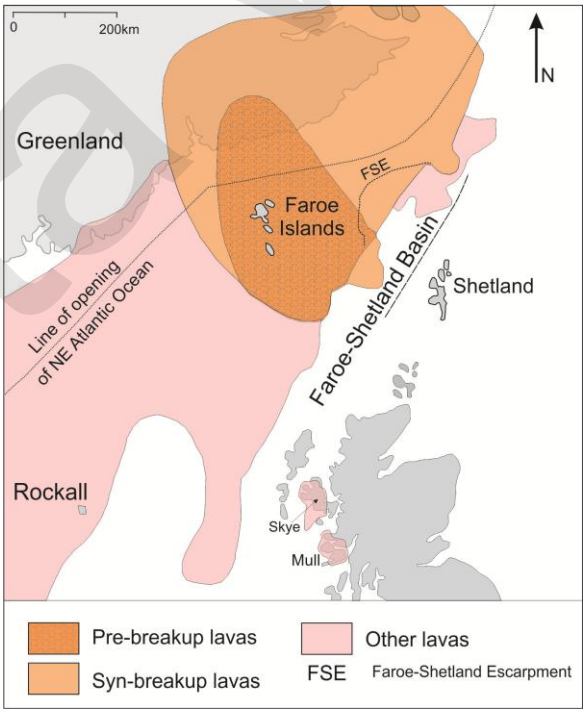


Figure 5-3: Distribution of lava sequences in the NE Atlantic (after Larsen *et al.* 1999).

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The characteristic magmas of the HIP are typically transitional to tholeiitic (MORB-like) basalt and their more-evolved products (trachyte and rhyolite), although relatively depleted in incompatible elements, indicating a depleted upper mantle source (Chapter 10).

This magmatism faltered and ultimately ceased as the lithosphere ruptured to the NW and ocean floor spreading commenced. Iceland is located atop the plume and continues to be the site of significant magma ascent, although considerably reduced from the Early Paleocene flux. The conjugate magmatic province, both in terms of igneous products and age, is located along the east coast of Greenland.

Most of the lava sequences, both offshore and onshore, erupted subaerially, predominantly from fissure-type feeders, now represented by laterally continuous linear dyke swarms (Figure 5-4; Figure 5-5) (Chapter 7). The NW-SE-trending dyke swarms that are associated with the Skye and Mull lava fields of western Scotland developed almost at right angles to the rift margin and indicate contemporaneous NE-SW extension of the NW European margin.

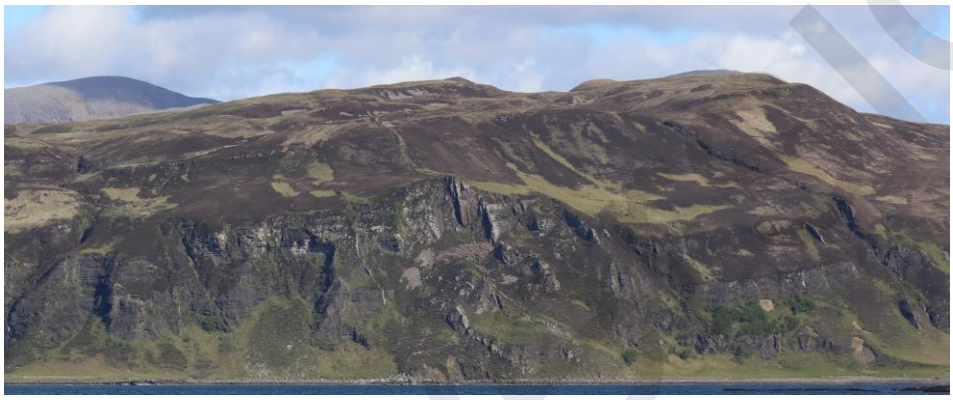


Figure 5-4: Members of the NW-SE -trending Skye Regional Dyke swarm standing proud of Lower Jurassic Pabby Shale Formation strata on the north coast of Loch Eishort, Strath, central Skye.

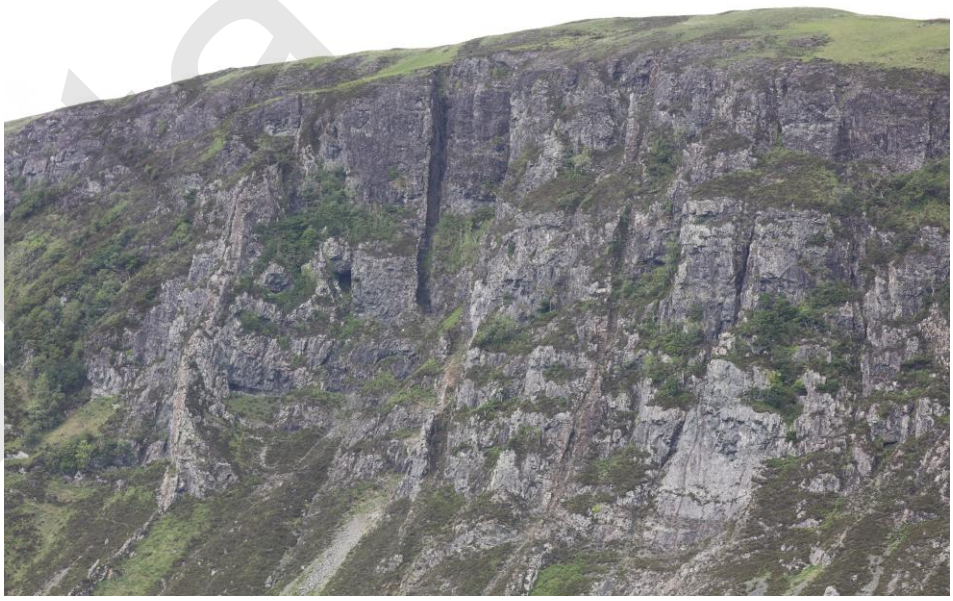


Figure 5-5: Members of the NW-SE -trending Mull Regional Dyke swarm within Paleocene lavas of the Crogan peninsula, SE Mull.

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Remnants of the two main lava fields form significant parts of Skye and Mull-Morvern (Figure 5-6; Figure 5-7), with isolated fragments present on the islands of Raasay, Scalpay, Canna with Sanday, and the NW part of Rum (outliers of the Skye Lava Field), and parts of Ardnamurchan and islands such as Ulva, Gometra, the Treshnish archipelago and Staffa (outliers of the Mull-Morvern Lava Field). The lavas that crop out on Eigg and Muck are remnants of a separate lava sequence.



Figure 5-6: Basaltic lavas of the Ramasaig Formation, forming the west-facing coastal cliffs of Biod Bàn above Oisgill Bay on the west side of Duirinish, Skye.



Figure 5-7: Lavas of the Staffa Lava Group, Binnein Ghorrie, on the south coast of the Ross of Mull, SW Mull. Many of these lavas have well developed columnar joints, indicative of eruption onto a wet substrate.

The St Kilda Central Complex, isolated *ca.* 75 km west of the Outer Hebrides, has no recognisable associated dyke-swarm (Figure 5-8).



Figure 5-8: A remnant of the isolated St Kilda Central Complex forming the islands of Boreray (right), Stac an Armin (left) and Stac Lee (middle).

The central complexes represent sites where magma emplacement into the upper continental crust along the rift margin reached anomalously large volumes (Figure 5-9). Along the NW European continental margin, the central complexes occur within a relatively narrow, N-S-trending zone *ca*. 40 km in width. The zone can be traced from Lundy, in the Bristol Channel, north through the central complexes in NE Ireland to those that occur along the western coast of Scotland. The St Kilda Archipelago is formed by a central complex that lies to the west of this zone. It is most appropriately grouped with the many putative submerged central complexes now recognised to the west of Shetland, which occur on the SE side of the Rockall Trough and within the Faroe–Shetland Basin (Ritchie & Hitchen 1996).

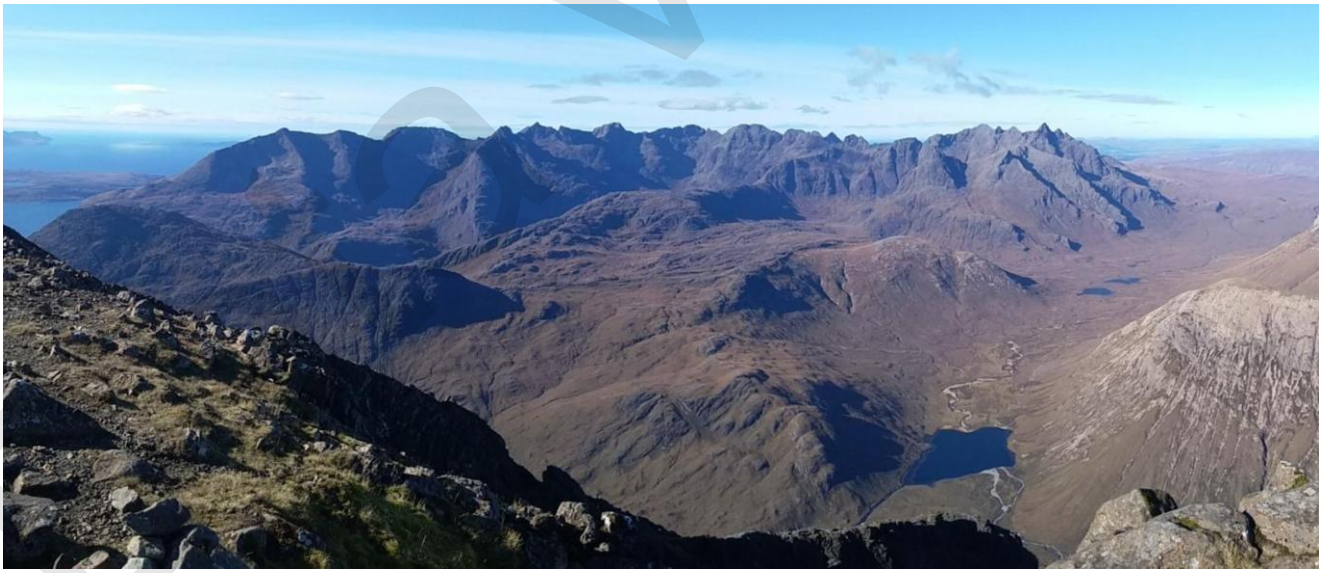


Figure 5-9: The Cuillin Intrusive Centre of the Skye Central Complex forms an arc of glacially sculpted gabbros and peridotites. View towards the west from Blà Bheinn.

In broad terms, the continental crust was thinned (stretched) during the initial stages of rifting and associated volcanic activity in a N-S zone running through western Britain and NE Ireland, and also farther to the west. Crustal extension permitted access to the Earth's surface for batches of mantle-derived

Pre-publication version

magmas; some erupted directly to the surface, whilst others ascended in stages, ponding at the mantle-crust boundary or in reservoirs at various levels within the crust.

The central complexes of western Scotland appear to be sited where older Palaeozoic (Caledonian) or Mesozoic structures cross this N-S zone (Chapter 4). For example, the North Arran Granite Pluton occurs on the trace of the Highland Boundary Fault, the Mull Central Complex occurs on the trace of the Great Glen Fault, and the Skye and Rum central complexes are situated on, or close to, the Camasunary–Skerryvore Fault. Typically, the central complexes occur within areas of basement rocks exposed in the elevated footwalls of Mesozoic faults (Roberts & Holdsworth 1999).

The lava fields of western Scotland are thickest within fault-bound basins containing syn-rift terrigenous Triassic sedimentary rocks (up to 500 m in thickness) overlain by marine to brackish Jurassic sandstones, limestones and mudstones (Binns *et al.* 1974; Walker 1979). The Skye Lava Field, comprising the thick sequences preserved on Skye, Canna, Sanday and Rum (Figure 5-10), is contained within the Sea of the Hebrides Basin, bounded to the NW by the Minch Fault. The sedimentary rocks of the basin have a feather edge against Lewisian and Torridonian rocks of the adjoining Skye–Rum Horst.



Figure 5-10: Sheet lavas (horizontally stratified) unconformably overlying Torridonian Supergroup strata (red-orange, inclined), forming Bloodstone Hill in NW Rum.

To the south, the Mull Lava Field is contained within the Inner Hebrides Basin, bounded to the NW by the Camasunary–Skerryvore Fault, with Precambrian rocks of the Skye–Rum Horst forming the footwall. This fault displaces lavas of the Eigg Lava Formation and Mull Lava Field/Group, but not those of the younger

Pre-publication version

Skye Lava Field/Group. The SE limit of the Inner Hebrides Basin was not fault-controlled, where lavas of the Mull Lava Field overstep Jurassic strata and remnants of overlying Cretaceous rocks to lie directly upon basement rocks of the Moine Supergroup north and south of Loch Sunart.

The Mull Lava Field is considered to extend north to include the thin sequence of lavas preserved in the Ben Hiant area on the south side of Ardnamurchan. The lava sequences of Muck and Eigg also appear to form a northern extension to the Mull Lava Field (Fyfe *et al.* 1993) and may be contemporaneous with the earlier part of that succession. The basaltic lavas on Eigg are capped by a thick rhyodacitic ignimbrite, which erupted into a palaeo-valley eroded into the earlier lavas. This ignimbrite is one of the youngest volcanic units preserved onshore in the HIP.

The latitude of the HIP in the Paleocene was not significantly different to that of the present-day, with a warm-temperate climate (Jolley 1997). The altitude of the lava fields varied, depending upon their rate of accumulation and their density-driven rate of subsidence. Palynological data from interbedded sedimentary units, including thin, low-grade coals, indicate a variety of plant habitats, from upland forests, to riparian, lacustrine and possibly estuarine; there is no evidence of open marine conditions (Jolley 1997). A generally wetter environment prevailed and enhanced the rate of weathering of the lava sequences, with the development of thick lateritic tops (palaeosols or boles) to lavas and derivative sediments dominated by ferruginous clay-rich materials.

Macrofossils are rare, but include fossil trees entombed within lavas, and wide-ranging assemblages of plant and insect fossils in the Leaf Beds of the Ardtun Conglomerate Member and other sedimentary units of the Staffa Lava Formation of the Mull Lava Field (Figure 5-11; Figure 5-12; Figure 5-13) (Campbell 1851; Gardner 1887; Bailey *et al.* 1924; Boulter & Kvacek 1989), the Allt Mòr, Glen Osdale (Figure 5-14) and Upper Fionchra members of the Skye Lava Field (Anderson & Dunham 1966; Williamson & Bell 1994; Emeleus 1997; Poulter 2011), and the Tallabric beds in SW Sanday (Figure 5-15), also of the Skye Lava Field. Where magma erupted into an aqueous environment, fragmental deposits, hyaloclastites, and pillowed lavas developed locally.



Figure 5-11: The Ardtun Conglomerate Member ('Leaf Beds'), Staffa Lava Group, at Biod an Sgairbh, north side of the Ross of Mull, SW Mull.

Be version

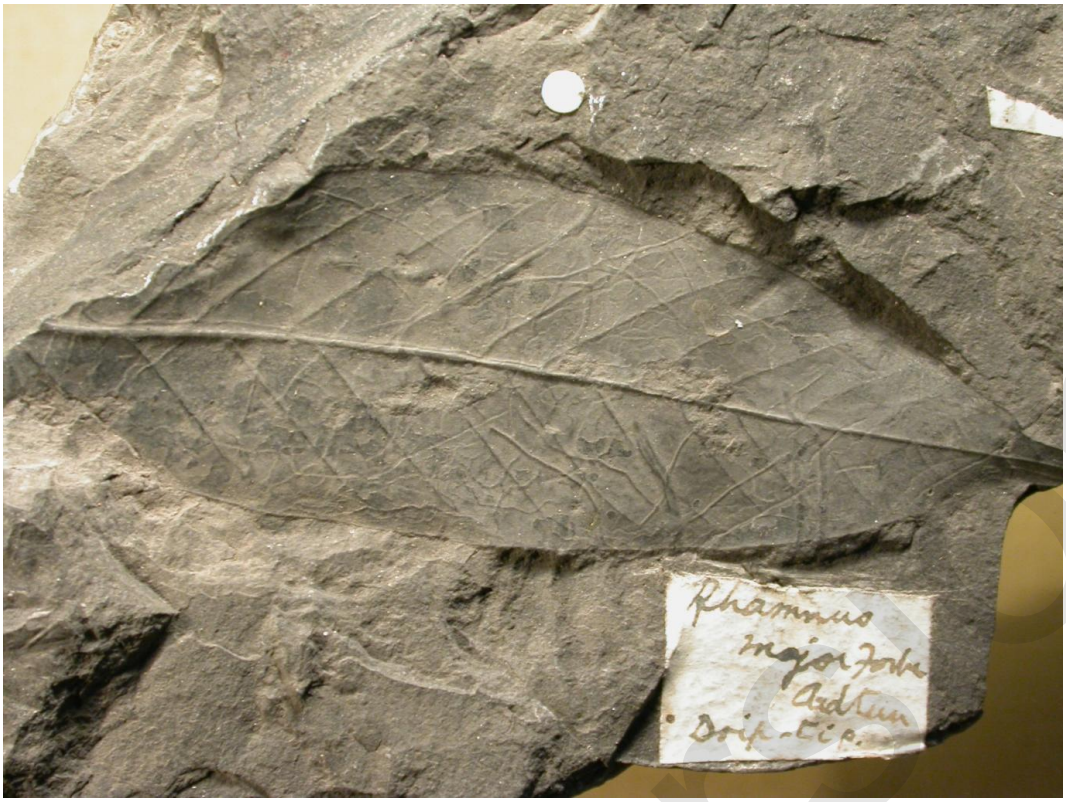


Figure 5-12: A leaf imprint of a buckthorn (Rhamnus) leaf from the Ardtun Leaf Beds, Staffa Lava Group, Biod an Sgairbh, north side of the Ross of Mull, SW Mull.



Figure 5-13: Thin beds of siltstone and coal within the upper part of the Staffa Lava Group at Codh' an Dunnain (Malcolm's Point) on the south side of the Ross of Mull. Ian Williamson for scale.

Public version



Figure 5-14: Laminated siltstones and mudstones of the Glen Osdale Member of the Skye Lava Field in the Osdale River, Duirinish. Pole *ca.*1 m long.



Figure 5-15: Leaf imprints within siltstones, Tallabric, SW Sanday. Pole *ca.* 1 m long.

The timing of emplacement of the linear regional dyke swarms relative to the lava fields is difficult to deduce directly from field relationships. There are few recorded examples of dykes feeding lavas and, at

the present level of erosion, on Skye, Mull, Muck, Eigg and in SE Rum, intense dyke swarms typically cut all of the lavas. Furthermore, on Skye, Rum and Mull, earlier members of the central complexes are commonly intruded by numerous NW-aligned dykes. However, from detailed mapping within the HIP (e.g. Williamson & Bell 1994; Williamson & Bell 2012) and throughout the NAIS (e.g. Upton 1988), it is likely that most of the lavas erupted from fissure systems, now represented by dykes, and from plugs developed on the dykes (Walker 1993; Kerr 1997).

The magmas were also intruded to form sill-complexes, which were preferentially developed in the sedimentary rocks of the Mesozoic basins. Only towards the ends of the individual pulses of igneous activity were lavas possibly erupted from more-localised volcanic edifices overlying the central complexes (e.g. Walker 1993; Bell & Williamson 2013).

5.3 Timing and Igneous Stratigraphy

The age of the lavas in relation to the central complexes can be deduced reasonably easily in some instances. Clear intrusive contacts between units of the central complexes and earlier/older lavas are common and are accompanied by pronounced high-grade thermal and hydrothermal aureoles (Figure 5-16; Figure 5-17; Figure 5-18**).** Conversely, where a lava field has developed after the emplacement of a central volcano *and* its subsequent exposure as a central complex by significant (1-2 km) erosion, there will be an erosional unconformity between the lavas and the exposed central complex; inter lava sedimentary deposits may contain material derived by erosion from the central complex (Figure 5-19).

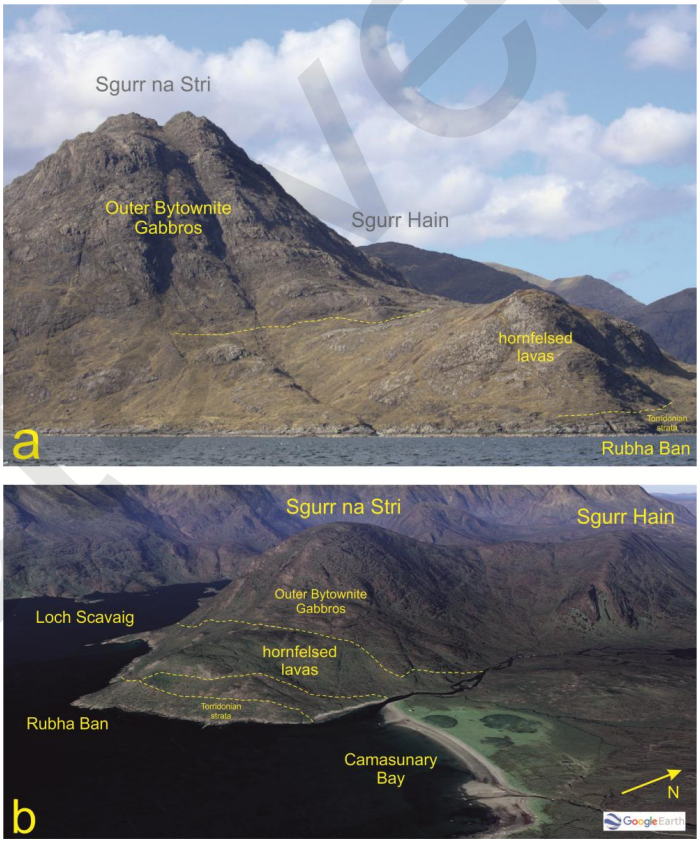


Figure 5-16: (a) The SE part of the Cuillin Intrusive Centre, emplaced into basaltic lavas, with an obvious cross cutting relationship and the development of a significant zone of hornfels of the lavas; and, (b) an annotated oblique Google Earth© image of the same area.

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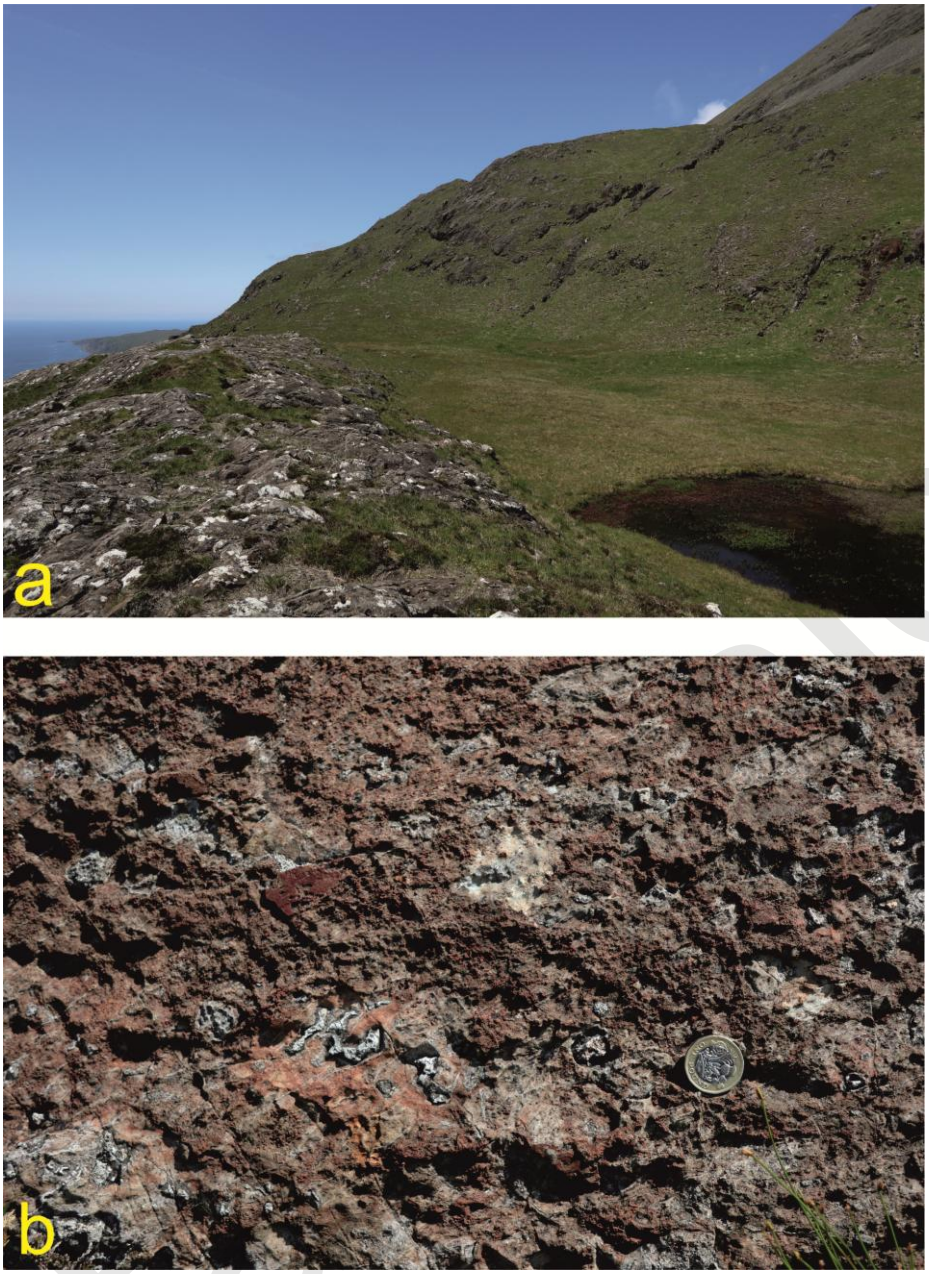


Figure 5-17: (a) The southern part of the Cuillin Intrusive Centre (right) emplaced into basaltic lavas (left), with a cross-cutting relationship and the development of a significant hornfels of the lavas; and, (b) detail of hornfelsed, amygdaloidal, basaltic lava, coin *ca.* 24 mm across.

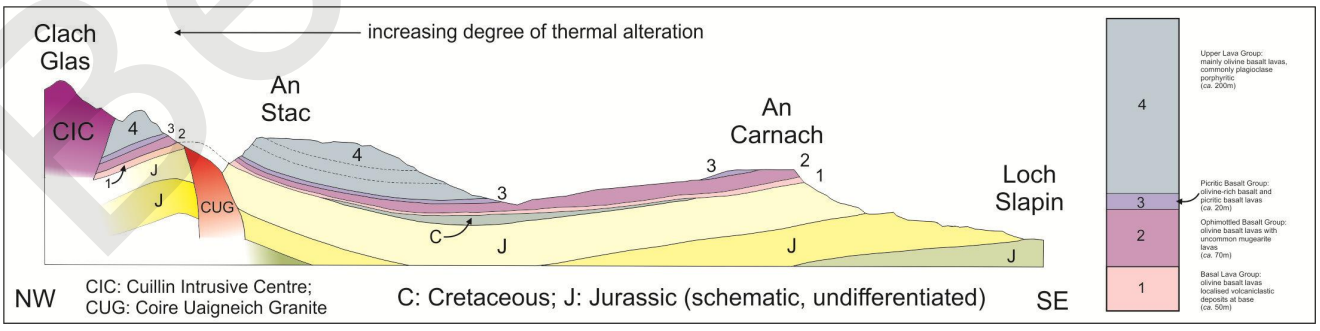


Figure 5-18: Stratigraphy of the north Strathaird lava sequence and general relationships of thermal/contact metamorphic effects (after Almond 1964).



Figure 5-19: Outliers of the Skye Lava Field in NW Rum. The sequence on Bloodstone Hill (far right) sits unconformably on Late Proterozoic Torridonian Supergroup strata; the sequence on Orval (far left) sits unconformably on the pale Paleocene Western Granite of the Rum Central Complex, demonstrating the relative ages of the two igneous units (lavas and central complex).

Intra-volcanic unconformities also provide valuable evidence for periods of erosion during the development of the lava fields (Figure 5-20)



Figure 5-20: The columnar-jointed, valley-filling, Paleocene Eigg Ignimbrite unconformably overlying stratified Paleocene basaltic lavas and sedimentary units, An Sgùrr, Eigg.

Beta version

Distinctive clast lithologies within sedimentary units within the volcanic sequences inform about lithologies exposed during the development of the lava sequence (Figure 5-21; Figure 5-22; Figure 5-23)



Figure 5-21: Paleocene boulder conglomerate (interbedded with basaltic lavas, not seen in this view) below the crags of An Sgùrr. The clast population is dominated by Paleocene basalt (lava) and Late Proterozoic Torridonian lithologies, together with uncommon fragments of Paleocene granite. Pole *ca.* 1 m long.



Figure 5-22: The Canna Lava Formation, a southern extension of the Skye Lava Field in SE Sanday, forming the rock pillar, Dùn Beag. Steep-sided palaeo-valleys within the lava field are filled with boulder conglomerates containing various lava field lithologies (basalt, hawaiite, mugearite etc.), together with fragments of granophyre that can be matched with the (therefore older than at least part of the lava field) Rum Central Complex.

Br...ver...on



Figure 5-23: Detail of the valley-filling boulder conglomerate at the base of Dùn Beag, SE Sanday. The most conspicuous boulders and cobbles are of dull brown basaltic lava and brick red Torridonian strata. Less common are fragments of granophyre derived from the Rum Central Complex. Pole *ca.* 1 m long.

The age relationships of the rocks within the HIP have not been fully resolved by radiometric and other age data. However, the relative ages are now becoming clearer through a combination of more precise radiometric dating techniques, palynological dating of interflow sedimentary rocks, and palaeomagnetism (e.g. Pearson *et al.* 1996; Bell & Jolley 1997; Hamilton *et al.* 1998; Chambers & Pringle 2001, Chambers *et al.* 2005). Published radiometric age determinations and biostratigraphical ages based upon palynofloral assemblages are summarised in Figure 5-24 and Figure 5-25. The lavas of the province span an interval of at least three million years, from *ca.* 61 Ma to at least 58 Ma. This interval corresponds to Chron 26R of the magnetic time scale (Berggren *et al.* 1995). All the Hebridean onshore central complexes appear to have been initiated during this interval, and it is apparently only in Skye, and possibly Mull, that significant activity occurred at later dates.

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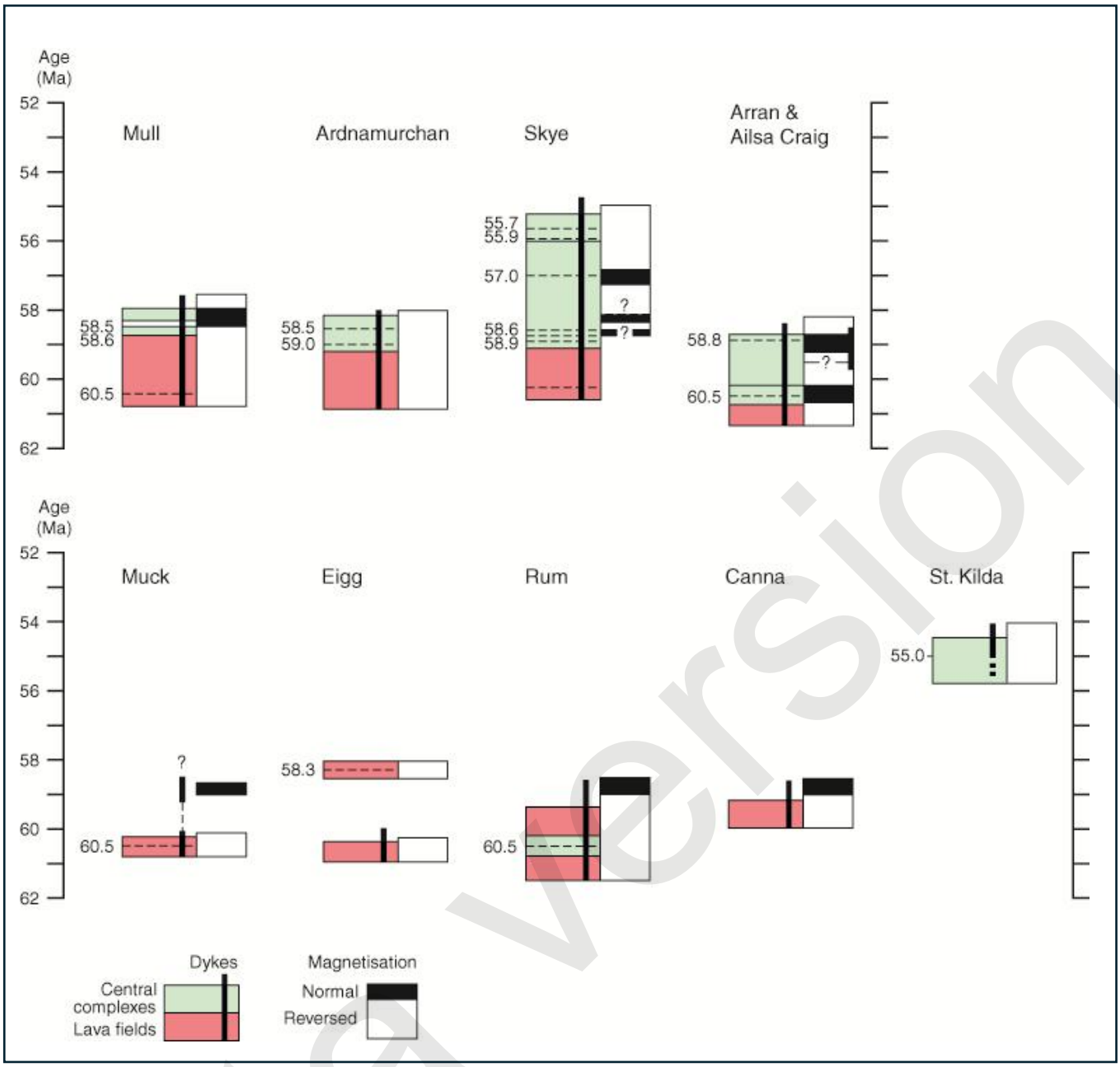


Figure 5-24: Isotope age data for volcanic and intrusive units of the HIP (after Emeleus & Bell 2005).

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Mull Central Complex			
Loch Ba Felsite, Centre 3	58.5 ± 0.1	U-Pb	*
	58.48 ± 0.18	Ar-Ar	6
Corra Bheinn Gabbro, Centre 2	58.3	U-Pb	*
Mull Lava Group			
Staffa Lava Formation	55–54.5	Palynology	3
	60.56 ± 0.29	Ar-Ar	6
Mull Plateau Lava Formation	58.35 ± 0.19	Ar-Ar	6
Trachytic tuff, Calgary Bay	60.57 ± 0.24	Ar-Ar	#
	60.5 ± 0.3	U-Pb	*
Skye Central Complex			
Eastern Red Hills Centre			
Beinn an Dubhaich Granite	55.89 ± 0.15	U-Pb	*
Pitchstone dyke cutting Beinn na Caillich Granite	55.7 ± 0.1	U-Pb	*
Western Red Hills Centre			
Marsco Granite	58.4 ± 2.1	U-Pb	*
Southern Porphyritic Granite	57 ± 0.5	U-Pb	*
Loch Ainort Granite	58.58 ± 0.13	Ar-Ar	6
Srath na Creitheach Centre			
Ruadh Stac Granite	57.5	Ar-Ar	5
Cuillin Centre			
Coire Uaigneich Granite	59.3 ± 0.7	Rb-Sr	4
Pegmatitic facies of Outer Gabbro, A1.	58.91 ± 0.08	U-Pb	2
Skye Lava Group			
Conglomerate underlying Talisker Formation, and other sedimentary rocks within Skye Lava Group	58.0–58.25	Palynology	3
Sleadale Trachytic Tuff, Skye Lava Group, below Preshal Beg Conglomerate Formation	58.91 ± 0.1	Ar-Ar	8
Canna Lava Formation			
Hawaiites	60.00 ± 0.23	Ar-Ar	7
Conglomerates within lavas, Rum and Canna	58.0–58.25	Palynology	3
Arran			
North Arran Granite Pluton	58.5, 58.4	Ar-Ar	5
Ardnamurchan Central Complex			
Great Eucrite, pegmatitic gabbro, Centre 3	59.05	Ar-Ar	5
Tonalite, Centre 3	58.6 ± 0.2	U-Pb	*
Rum Central Complex			
Alkaline segregation in Central Intrusion	60.53 ± 0.08	U-Pb	2
Biotite, pegmatitic facies of Western Layered Intrusion	60.1 ± 1.0	Ar-Ar	2
Western Granite	60.01 ± 0.45	Ar-Ar	7
Eigg Lava Formation			
Sanidine in tuff near base of formation on Muck	60.65 ± 0.07	Ar-Ar	7,1
Zircon in same tuff	61.15 ± 0.25	U-Pb	7
Sgurr of Eigg Pitchstone Formation			
Pitchstone lava	58.72 ± 0.07	Ar-Ar	7

All radiometric age determinations quoted at the 2 sigma level, except for references 5 and 6 which are at the 1 sigma level.
References: 1 Pearson et al., 1996; 2 Hamilton et al., 1998; 3 Jolley, 1997; 4 Dickin, 1981; 5 Chambers, 2000; 6 Chambers and Pringle, 2001; 7 Chambers et al., 2005; 8 Bell and Williamson, 2002
* unpublished U-Pb analyses by M A Hamilton, Jack Satterly Geochonology Laboratory, Department of Geology, University of Toronto
# unpublished Ar-Ar analysis by S P Kelley (Open University)

Figure 5-25: Isotope age data for volcanic and intrusive units of the HIP.

Beta version

There is only one precise radiometric age determination for the Skye Lava Field, although there is a considerable body of palynological data. The Portree Hyaloclastite Formation (Palagonite Tuffs of Anderson & Dunham 1966) at the base of the Skye Lava Group and the Preshal Beg Conglomerate Formation close to the top of the group (Bell & Williamson 2013) contain pollen assemblages that indicate an age range of 58.25 to 58.0 Ma. (Jolley 1997), and an Ar-Ar age of 58.91 ± 0.18 Ma has been obtained from the trachytic Sleadale Tuff beneath the Preshal Beg Conglomerate (Bell & Williamson 2002). The petrologically distinct intra-canyon lava of the Talisker Formation, which directly overlies the Preshal Beg Conglomerate Formation, is the youngest lava within the Skye Lava Field. Although the Talisker lava and the Preshal Beag conglomerates are separated from the underlying lavas by a clear erosional break, which coincides with a significant change in magma-type, the time interval represented was probably short (Hamilton *et al.* 1998).

The lavas of the Canna Lava Formation, preserved in NW Rum, which belong to the Skye Lava Group (Williamson & Bell 1994; Emeleus 1997), are demonstrably younger than the Western Granite, one of the earliest members of the Rum Central Complex (Chapter 9). These lavas overlie a weathered surface of the granite, and interstratified conglomerates on Rum, Canna, Sanday and SW Skye contain clasts derived from the granite and from other, younger, members of the Rum Central Complex. Thus, the lavas erupted in an interval of less than 1.6 million years, between the emplacement and unroofing of the Rum Central Complex (60.5 - 60.1 Ma) and the emplacement of the gabbros of the Cuillin Intrusive Centre on Skye (58.9 Ma), which intrude the Skye Lava Group.

In the Small Isles, the lava-like ignimbrite that forms the ridge of An Sgùrr is one of the latest eruptive units in the HIP (58.7 Ma), whereas the tuffs at the base of the Eigg Lava Formation on Muck give the oldest age (60.6 Ma). Neither formation has yet yielded useful material for palynological dating, although plant remains are well known from conglomerates beneath the An Sgùrr ignimbrite.

The Mull Lava Field is intruded by the Mull Central Complex. Radiometric age determinations and geochemical signatures (Chambers & Pringle 2001) indicate that construction of the Mull and Skye lava fields may have been penecontemporaneous. This is, however, difficult to reconcile with the palynological data. The Mull flora constitutes a widely recognised, well-defined and short-lived assemblage that flourished in warm, subtropical conditions, the Late Paleocene Thermal Maximum (LPTM), and is completely different from the older flora obtained from Skye and the Small Isles (Jolley 1997). The LPTM is dated at 54.98 Ma on the geological time scale of Berggren *et al.* (1995); the Mull sedimentary units containing the diagnostic pollen flora are overlain by lavas that have yielded isotopic U-Pb and Ar-Ar dates between 57.5 and 60.54 Ma (e.g. Chambers & Pringle 2001). Furthermore, within the post-lava Mull Central Complex, the Corra-bheinn Gabbro and Loch Bà intrusions are dated by the U-Pb method at 58.3 and 58.5 Ma, respectively (Hamilton *et al.* 1998).

The Skye Central Complex contains many intrusive units, the oldest of which are layered gabbroic and ultrabasic rocks, together with several confluent cone-sheets that comprise the Cuillin Intrusive Centre (Chapter 9). A U-Pb age of 58.9 Ma has been obtained from a gabbroic pegmatite formed early in the development of this intrusive centre. Amongst the cone-sheets is a relatively late-stage suite of dolerites and basalts, which were emplaced at very shallow depths, and are compositionally identical to the lava of the Talisker Formation (Walker 1993b; Bell *et al.* 1994). It may therefore be inferred that the later stages in the development of the Cuillin Intrusive Centre, which represents the eroded roots of a basaltic central volcano, were synchronous with and relate to the outpouring of the distinctive lava of the Talisker Formation (Figure 5-26) (Bell & Williamson 2013).

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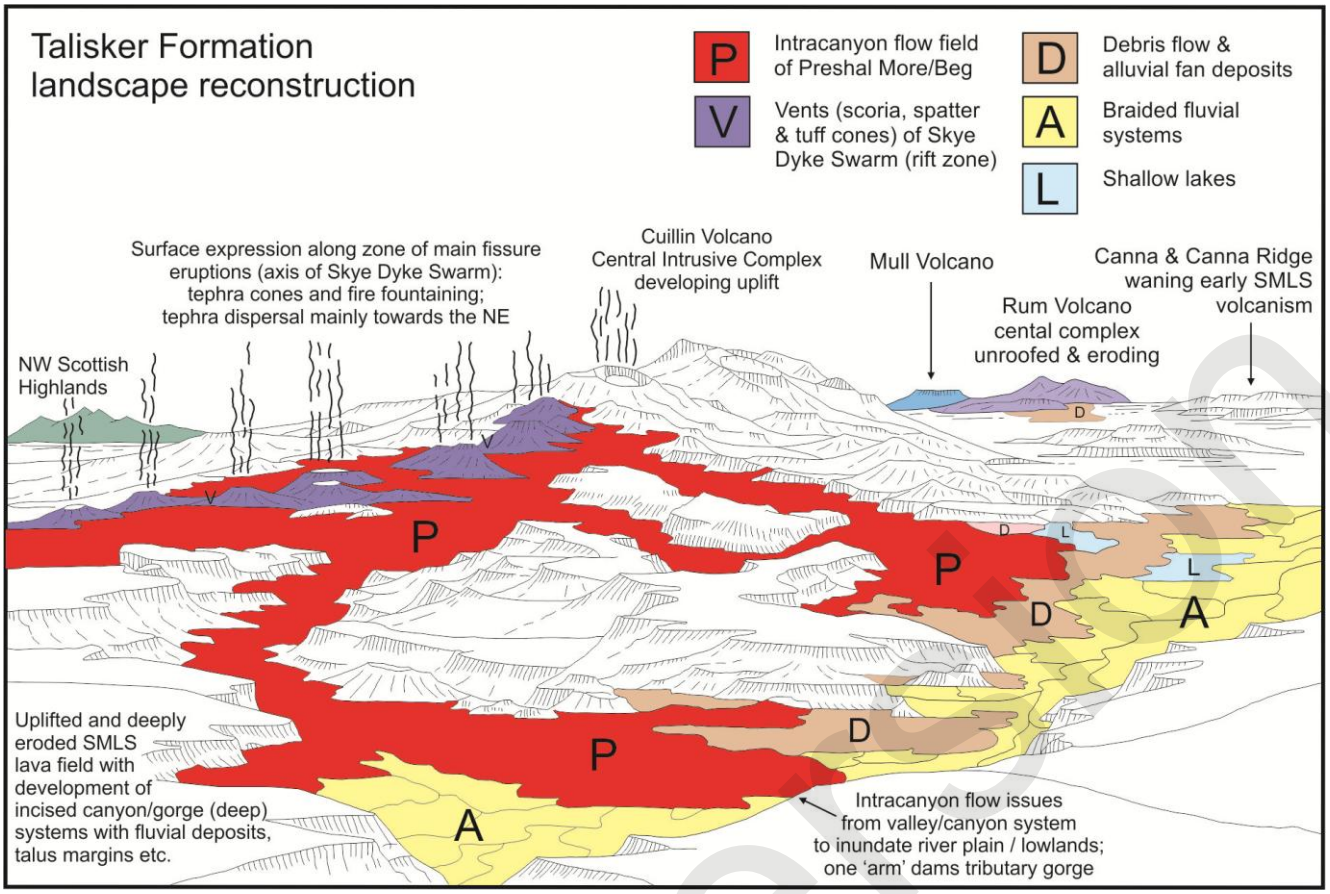


Figure 5-26: Schematic Talisker Formation intra-canyon lava landscape reconstruction (from Bell & Williamson 2013).

The Talisker lava flowed onto a land surface formed from older and compositionally different formations of the Skye Lava Group. There is a close correspondence between the radiometric age for early intrusive activity in the Cuillin Intrusive Centre and that for the eruption of the trachytic tuff underlying the Preshal Beg Conglomerate Formation, and the biostratigraphical age of the Preshal Beg Conglomerate Formation (Figure 5-27; Figure 5-28). Consequently, the Cuillin Intrusive Centre was developing contemporaneously with at least part of the Skye Lava Field.

Beta version



Figure 5-27: The Preshal Beg Conglomerate Formation on the north side of Preshal Beg, Minginish, SW Skye. Within fine-grained strata are distinctive palynological materials from which precise age dates have been obtained (Jolley 1997). Ian Williamson for scale.



Figure 5-28: Poorly exposed trachyte tuff in the unnamed burn NW of the Preshal Beg outcrop of the Talisker Formation lava. Although of a distinctly weathered appearance in hand-specimen, this material is remarkably fresh and has provided an isotopic age of 58.91 Ma.

Preliminary version

The younger granite centres of the Skye Central Complex yield ages that range from *ca*. 58.5 to 57 Ma for intrusions of the Srath na Crèitheach and Western Red Hills intrusive centres, to *ca*. 56 Ma for the Beinn an Dubhaich Granite and a rhyolitic vitrophyre ('pitchstone') dyke that intrudes the nearby Beinn na Caillich Granite, both belonging to the Eastern Red Hills Intrusive Centre (Figure 5-25). These ages suggest that the growth of the Skye Central Complex may have spanned up to three million years, compatible with the complex palaeomagnetic record.

The Ardnamurchan Central Complex was emplaced into basaltic lavas. No reliable age data are available for these hydrothermally altered lavas, although those around Ben Hiant, along the eastern side of the central complex, are an outlier of the Mull–Morvern Lava Field. Radiometric age determinations for the Great Eucrite and tonalite intrusions of Centre 3 give ages of *ca*. 59 Ma (Chapter 9) (Figure 5-25; Figure 5-29).



Figure 5-29: Oblique Google Earth© image of Ardnamurchan and field views of the Great Eucrite, one of the Centre 3 gabbroic intrusions, locally with well-developed stratification. The arrow indicates the direction of view. Pole *ca*. 1 m long.

The radiometric age of 60.6 Ma obtained from the oldest lavas in the Eigg Lava Formation is comparable to those from rocks near to the base of the Mull Lava Field (Figure 5-25). Investigations of the offshore geology between western Mull, Ardnamurchan and the Small Isles suggest that the lavas of Mull are linked to those of Muck and Eigg (Fyfe *et al.* 1993).

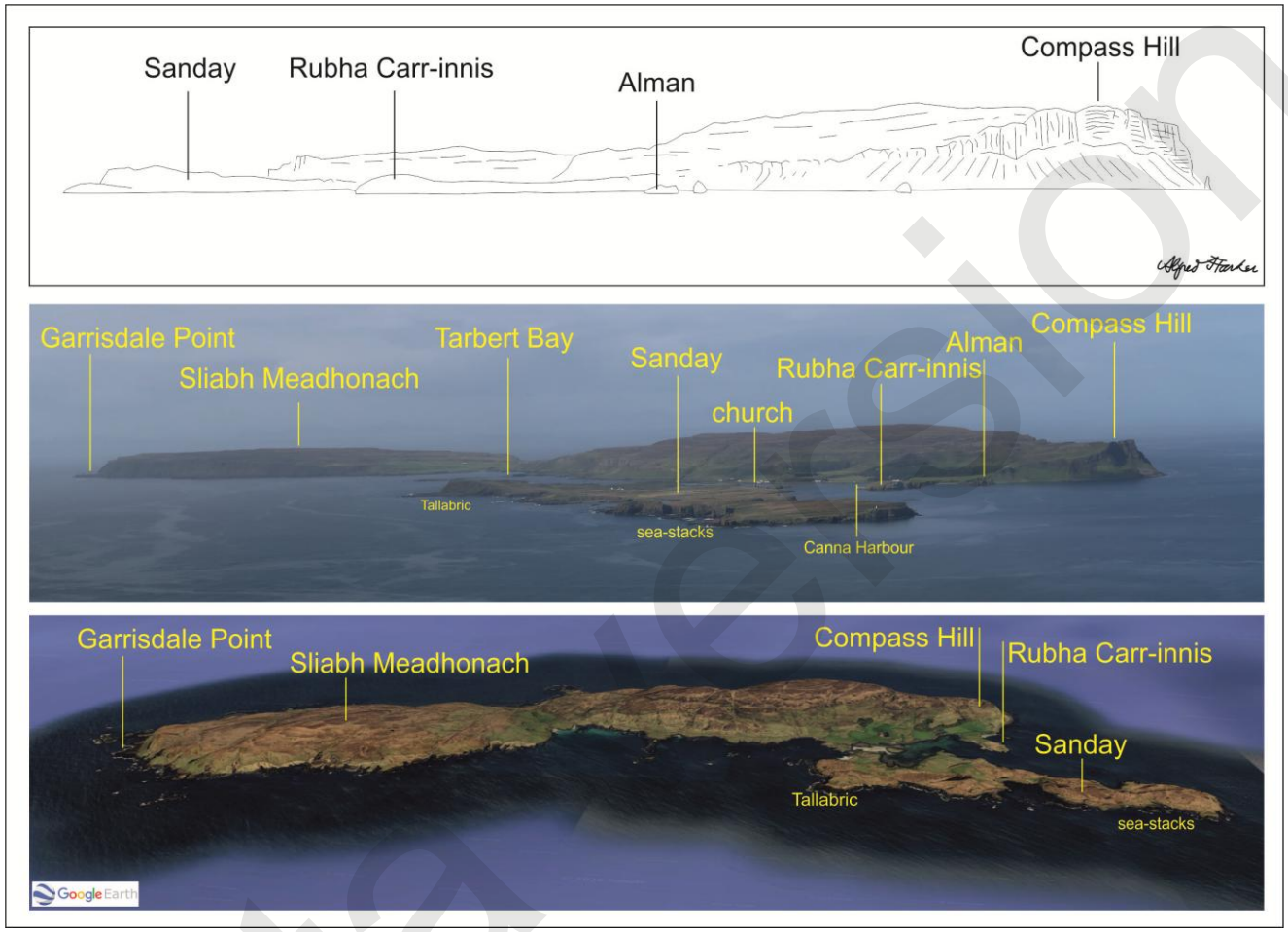
The episodes of lava eruption in the HIP, summarised in Figure 5-25, appear to constitute discrete pulses within a period of less than three million years. However, the age and duration of activity within the central complexes are currently less well constrained. The Rum Central Complex postdates the Eigg Lava Formation but predates the Skye Lava Group. The majority of the Skye Central Complex most likely post-dates the Skye Lava Group, but the young Talisker Lava Formation may have been erupted from a central volcano now represented by parts of the Cuillin Intrusive Centre. The Mull Central Complex postdates the Mull Lava Group. The St Kilda Central Complex, the Blackstones Central Complex, the North Arran Granite Pluton, the Central Arran Ring-complex and the Ailsa Craig Granite have all been dated by radiometric techniques, but some have significant errors. They also have the limitation of not being associated with lavas to offer a precise comparison with pollen and spore age data.

Evidence that the plume-driven igneous activity in the HIP occurred sporadically rather than continuously may be provided by the temporal spacing of detritus fans in offshore Paleocene sedimentary rocks (White & Lovell 1997). These fans resulted from increased uplift and erosion of the sedimentary source areas, which may, in turn, have been caused by pulses of magmatic underplating from a mantle plume. Such underplating may also have triggered the igneous activity, as the correlation between major periods of fan deposition and maxima in igneous activity in the HIP is quite striking. The very clear break in magmatism between emplacement of the Rum Central Complex and accumulation of the Canna Lava Formation could be one result of pulsed activity.

Beta version

6 Paleocene lava fields and associated sedimentary rocks

6.1 Introduction



Lavas and sedimentary units, Canna and Sanday

Following the formation and infilling of the Mesozoic basins, a major rifting event commenced in the Early Selandian (stage) of the Paleocene Epoch as a precursor to the commencement of ocean floor spreading in the NE Atlantic Ocean at *ca*. 55 Ma.

Within the Hebridean Igneous Province (HIP), this major magmatic event began with the construction of lava fields (Figure 6-1; Figure 6-2; Figure 6-3), emplaced predominantly into a terrestrial environment, and erupted from fissures now expressed by NW-SE -trending dyke swarms (Chapter 7); less commonly, eruptions were into lakes and river channels. On Skye, locally, the earliest eruptions were into shallow water, leading to the development of pillow lavas and hyaloclastite deposits; later eruptions into fluvial channels also resulted in similar materials (Figure 6-4; Figure 6-5; Figure 6-6). Thin, non-marine, clastic sedimentary units and coals occur throughout the volcanic sequences. One of the latest volcanic events was the eruption of a lava-like rhyodacite ignimbrite into a river channel, now forming the (inverted topographic) ridge of An Sgùrr on the island of Eigg (Figure 6-7).

Beta version



Figure 6-1: Columnar-jointed basaltic lavas of the Skye Lava Field at A' Chill, south Canna.

Beta version



Figure 6-2: Basaltic lavas of the Mull Lava Field forming the cliffs at Cada an da Luain, Brolass, SW Mull, illustrating the complexity of the HIP volcanic sequence and their contrasting inland expression, devoid of detail.



Figure 6-3: Basaltic lavas of the Beinn Edra Group forming the Trotternish Escarpment at the Quiraing, Trotternish, north Skye.

Pre-publication version



Figure 6-4: Basaltic pillow lavas, Creag Mhòr, north side of Portree Bay, Skye. Ruler 30 cm long. Bases of pillows outlined in general view. Colourised image used to distinguish discrete pillows.



Figure 6-5: Hyaloclastites at the base of the Skye Lava Field, Craig Ulatota, north of Portree. Pole *ca.* 1 m long.



Figure 6-6: Base of the Talisker Formation intra-canyon lava, with normal, columnar-jointed material overlying pillow facies material (crossed by walking pole), overlying the Preshal Beg (boulder) Conglomerate Formation. SE side of Preshal Beg. Pole *ca.* 1 m long.



Figure 6-7: The south side of the ridge of An Sgùrr, south Eigg, a remnant of a valley-fill, lava-like rhyodacite ignimbrite.

6.2 General characteristics of the lava fields

Remnants of two significant lava fields are recognised: the Skye Lava Field (Anderson & Dunham 1966; Williamson & Bell 1994; Bell & Williamson 2002, 2024) and the Mull Lava Field (Bell & Williamson 2002, 2024; Williamson & Bell 2012) (Figure 6-8; Figure 6-9). The lavas on the islands of Eigg and Muck are interpreted as being a third sequence, the Eigg Lava Formation, not related to either of the Skye or Mull lava fields (Emeleus 1997; Bell & Williamson 2002, 2024).

The Skye Lava Field crops out on Skye, together with, to the south, the islands of Canna, Sanday and (NW) Rum (Figure 6-10; Figure 6-11; Figure 6-12). The Mull Lava Field crops out on Mull, its many small offshore islands, including Staffa and Ulva, together with the sequences on Morvern and on Ardnamurchan, both on the Scottish Mainland.

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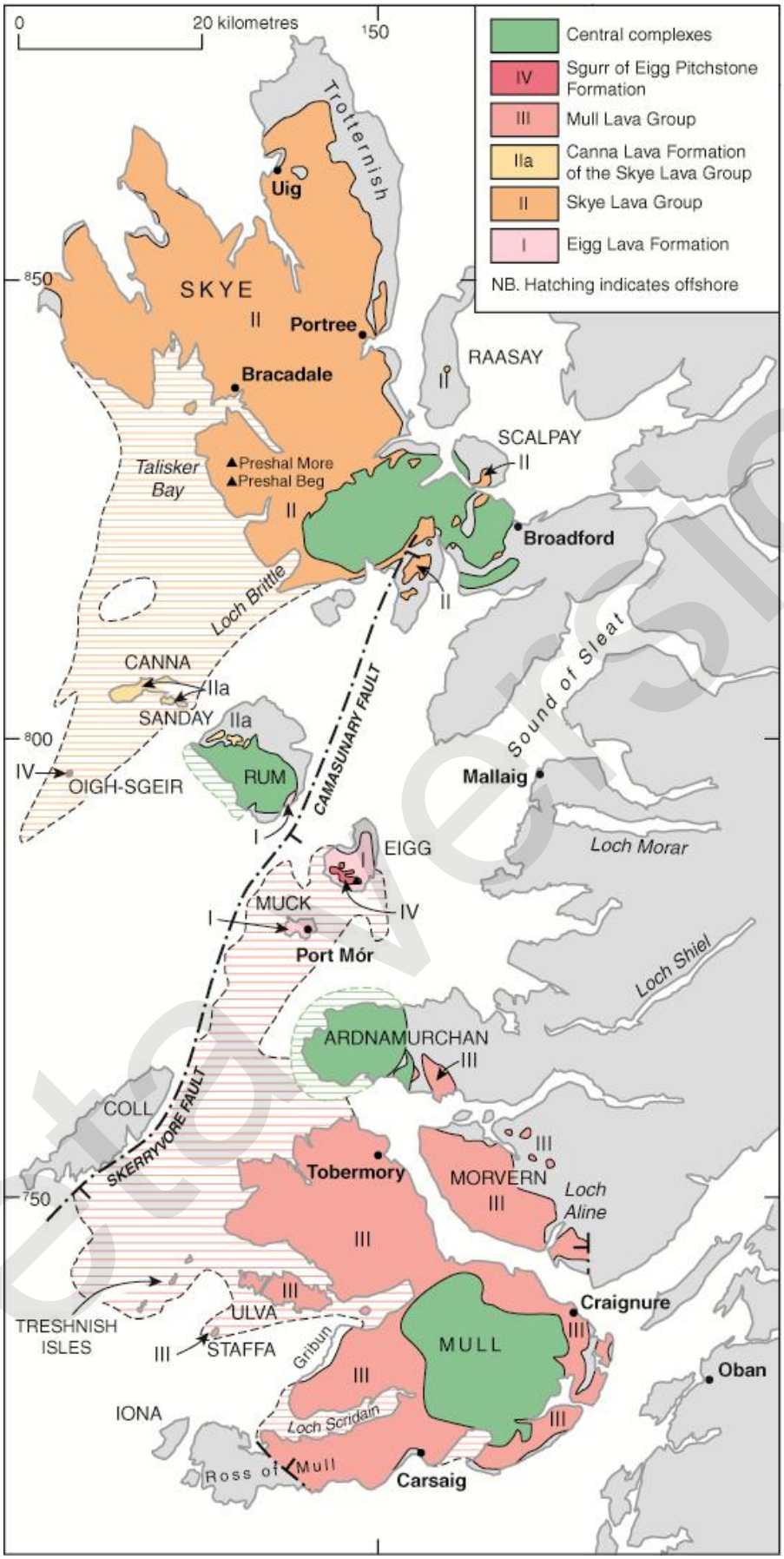


Figure 6-8: Paleocene lava fields of the Hebridean Igneous Province (HIP). Not shown are masses of lavas (mainly basaltic) within the central complexes (after Emeleus & Bell 2005).

Beta version

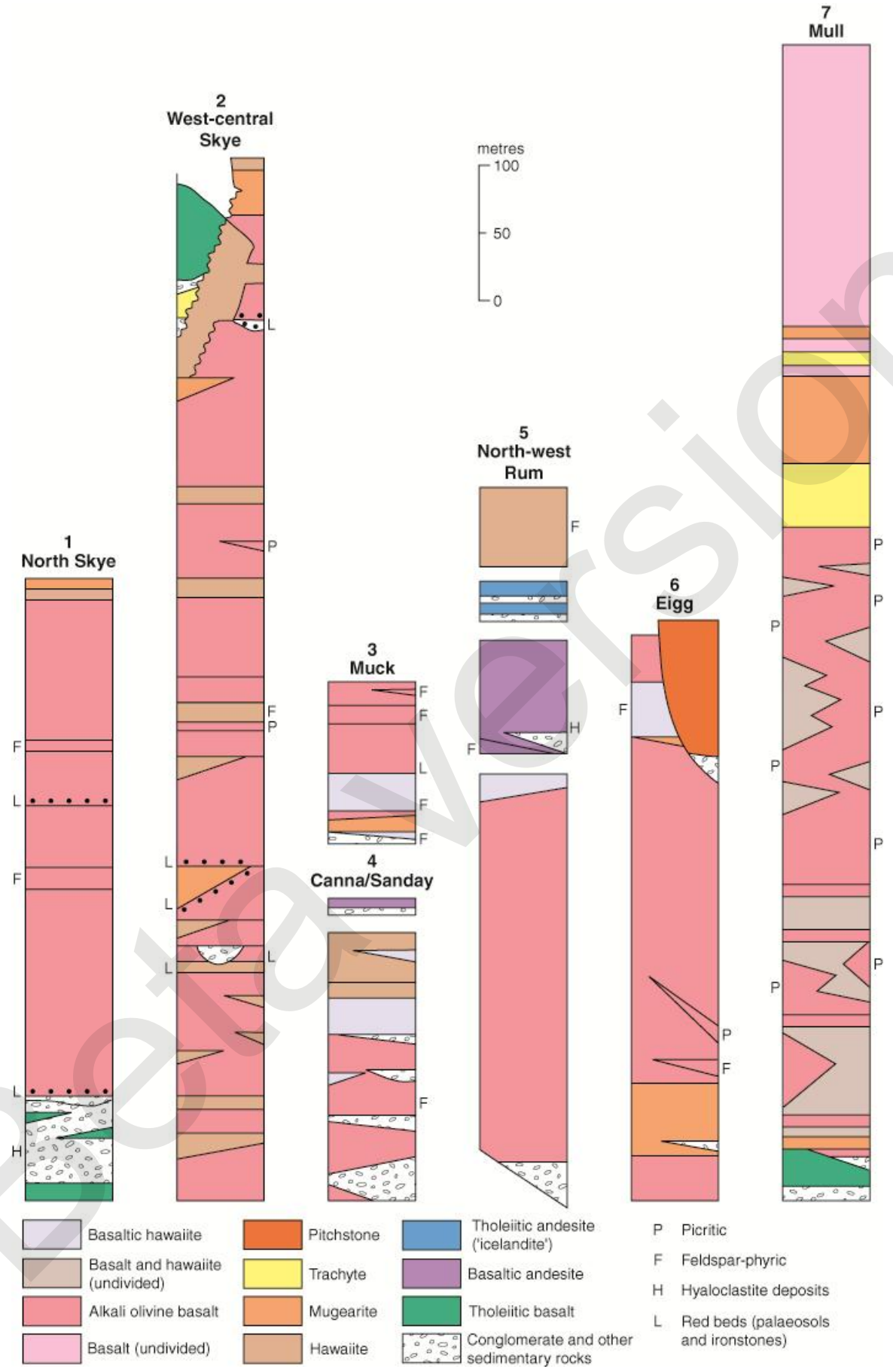


Figure 6-9: Generalised and composite vertical sections of the lava fields in the Hebridean Igneous Province (after Emeleus & Bell 2005).

Beta version



Figure 6-10: Outliers of the Skye Lava Field on NW Rum, forming the summits (left-to-right): Fionchra, the ridge of Orval, and Bloodstone Hill, overlying Late Proterozoic Torridonian Supergroup sandstones, the Paleocene Western Granite, and Late Proterozoic Torridonian Supergroup sandstones, respectively. Viewed towards the SE. from Canna.



Figure 6-11: An outlier of the Skye Lava Field on NW Rum, forming the coastal cliffs of Bloodstone Hill, NW Rum, overlying Late Proterozoic Torridonian Supergroup sandstones. View towards the SE. Height of cliff *ca.* 350 m.

Preview version



Figure 6-12: Beinn na h-Uamha, left of centre, an outlier of the Mull Lava Field, on Morvern. View towards the SE across Loch Sunart from Ben Hiant. In the near ground (left) are horizontal lavas of the Ardnamuchan outlier.

The post-Jurassic to pre-Paleocene rock record within the HIP is limited to small, scattered outcrops of Upper Cretaceous (Cenomanian) strata (Chapter 3). The succeeding strata, volcanic and sedimentary, are of Paleocene age (predominantly Paleocene), although precise and accurate ages are yet to be determined (Chapter 5). The base Paleocene angular unconformity is complicated, with a wide variety of underlying pre-Paleocene rocks present (Figure 6-13; Figure 6-14; Figure 6-15; Figure 6-16; Figure 6-17; Figure 6-18). There is very little relief on the unconformity, suggesting that the pre-volcanic landscape was relative subdued, although evidence for a true peneplain is lacking. The base of the lava field is not always above present-day sea level.



Figure 6-13: Base lava field unconformity on the south coast of Mull at Sròn nam Boc, west of Carsaig Bay, with dark Paleocene columnar-jointed, basaltic lavas overlying pale Jurassic sandstones. All cut by Paleocene minor intrusions. Height of cliff *ca*. 200 m.

Browser version



Figure 6-14: Detail of base lava field unconformity on the south coast of Mull at Sròn nam Boc, west of Carsaig Bay, with dark Paleocene columnar-jointed, basaltic lavas overlying pale Jurassic sandstones.



Figure 6-15: Base lava field unconformity on the south coast of the Laggan peninsula, SE Mull, at An Garradh, with dark Paleocene basaltic lavas overlying pale Jurassic sandstones. All cut by Paleocene minor intrusions.

Beta version



Figure 6-16: Base lava field unconformity on the south coast of the Laggan peninsula, SE Mull, at An Garradh, with dark Paleocene basaltic lavas overlying pale Upper Cretaceous and Jurassic sedimentary rocks, all cut by Paleocene minor intrusions.



Figure 6-17: Base lava field unconformity, with rubbly basaltic breccia (hyaloclastite) of the Skye Lava Field intruded by basalt and dolerite sheets, overlying Mesozoic strata (at base of cliff) on the north side of Soay Sound at Suidhe na h-Inghne, west of the outflow of the Allt na Meacnaish.

Beta version



Figure 6-18: Base lava field unconformity, with a basaltic lava of the Skye Lava Field intruded by basalt and dolerite sheets, overlying Mesozoic strata (at base of cliff) on the north side of Soay Sound at Suidhe na h-Inghne, west of the outflow of the Allt na Meanaish.

Intra lava field unconformities are recognised, indicating periods of erosion, albeit locally, and the formation of drainage systems (Figure 6-19; Figure 6-20).



Figure 6-19: A remnant of the thick (at least 120 m) intra-canyon lava of Preshal More, Minginish, SW Skye. The older volcanic sequence on which the drainage system developed is represented by the horizontally stratified units on the left. The topographic unconformity defines the canyon system into which the lava erupted.

Beta version



Figure 6-20: The (unconformable) base of the valley-fill lava-like ignimbrite on the island of Eigg, overlying clastic sedimentary units, conglomerates and sandstones, deposited within the valley system that was eroded into the underlying volcanic sequence.

The presence of sedimentary units, especially fine-grained lithologies such as mudstones and siltstones, also mark hiatuses in lava field aggradation and, where laterally traceable, can act as useful time markers (Figure 6-21; Figure 6-22; Figure 6-23).

Beta version



Figure 6-21: A pale, thin, intra-volcanic siltstone-mudstone-coal sequence within the oldest part of the Mull Lava Field, the Staffa Lava Formation, Codh' an Dùnain, south Brolass, SW Mull. Ian Williamson for scale.



Figure 6-22: Cross-bedded flint conglomerate overlying (dark) volcaniclastic strata forming the Pulpit Rock, within the lava sequence east of Malcolm's Point, Brolass, SW Mull. Ian Williamson for scale.

Preview version



Figure 6-23: A columnar-jointed basaltic lava overlying conglomerates and sandstones within the Skye Lava Field sequence at Compass Hill, east Canna.

The fossil record is understandably poor, as the relatively uncommon interbedded sedimentary rocks are of terrestrial character, with only fossil plants (mainly leaves), together with pollen and spore data from the finer-grained lithologies, siltstone and mudstone, providing useful age and environmental indication (Figure 6-24; Figure 6-25; Figure 6-26; Figure 6-27) (Jolley 1997). Palynoflora data indicate a generally warm temperate climate and marked a period of significant cooling following the tropical conditions of the Late Cretaceous. Where Upper Cretaceous (Maastrichtian) chalk is preserved below the lavas, for example in west and SW Mull and on Morvern, residual deposits of 'clay with flints' occur, together with a karstic surface with a relief of up to several metres. Elsewhere, further evidence of pre-lava relief is provided where Paleocene, coal-bearing strata and channel-fill conglomerates typical of fluviatile environments are preserved locally within small pockets between the lavas.

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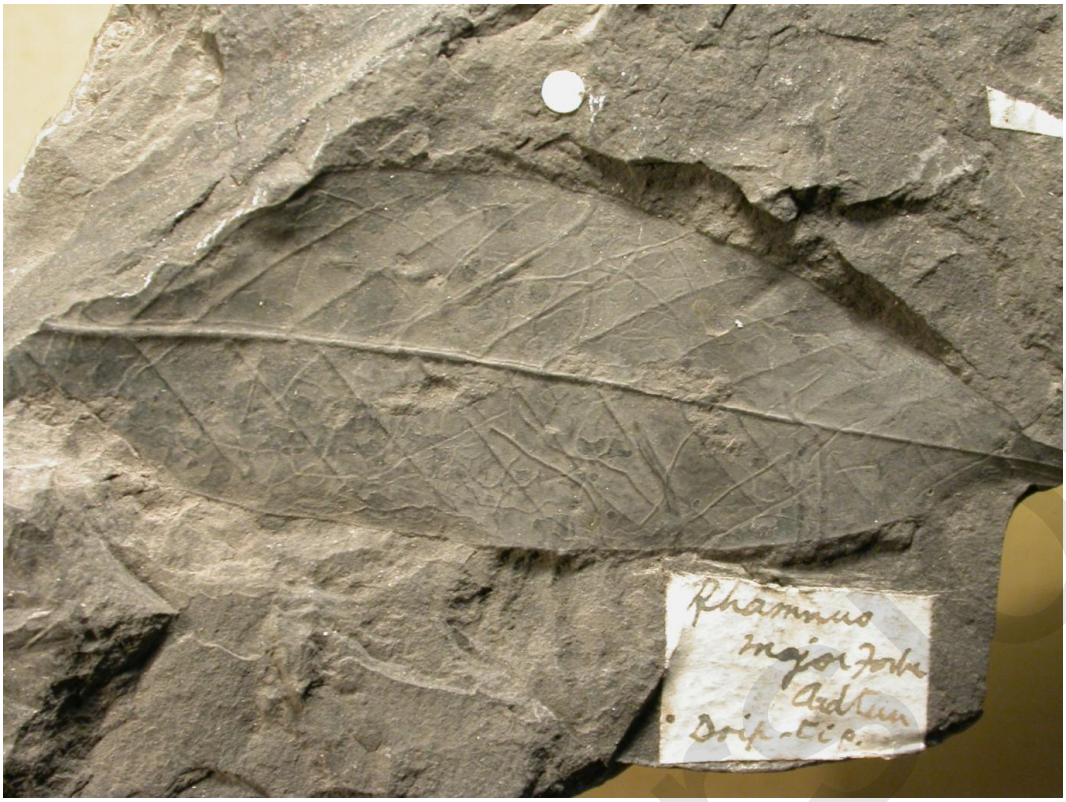


Figure 6-24: A leaf imprint of a buckthorn (Rhamnus) leaf from the Ardtun Leaf Beds, Staffa Lava Group, Biod an Sgairbh, north side of the Ross of Mull, SW Mull.



Figure 6-25: Horizontal fossil tree (cast made of basalt), coastal section between Quinish Point and Dùn Leathan, Quinish, NW Mull.

Review version



Figure 6-26: Conglomerates grading upward into pebbly sandstones and siltstones; some freshwater limestones, interbedded with columnar-jointed basaltic lavas of the Staffa Lava Formation, at 'The Ladder', south of Macculloch's Tree, Ardmeanach, SW Mull. Hammer, located on sedimentary section at top of ladder for scale, *ca*. 50 cm long.



Figure 6-27: Interbedded sandstones and siltstones with leaf imprints, invaded by a lava lobe within the sequence in the Allt Mòr, Minginish, west-central Skye. Hammer *ca*. 50 cm long.

The initial phases of volcanic activity in both the Skye and Mull lava fields were marked by the eruption of basaltic scoria from fissure-controlled cones, and by the subsequent extrusion of lavas into shallow water, with the formation of hyaloclastite and tuff deposits (Figure 6-28). Magma was also intruded as

shallow sills into unconsolidated, water-saturated sediments (mainly silt and mud) of Paleocene age. On Mull, the presence of basaltic pillow lavas has been used to infer the presence of a water-filled caldera during the development of a later central volcano (Bailey *et al.* 1924).



Figure 6-28: Degraded (weathered) basaltic tuff at the base of the Skye lava Field, Lòn Druiseach, south Trotternish, Skye.

Pauses in the predominantly subaerial volcanic activity are marked by the development of weathered tops to lavas, some of which pass up into relatively thick and laterally continuous red (oxidised) palaeosols (boles) and clastic units (Figure 6-29; Figure 6-30; Figure 6-31). It was during these periods that lacustrine sediments (clay, silt and peaty mire) accumulated in shallow depressions on the land surface, together with fluviatile channel-fills that formed condensed sequences of conglomerate, sandstone, siltstone and coal (Figure 6-32; Figure 6-33; Figure 6-34).

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Figure 6-29: Sequence of basaltic lavas with weathered tops (bright red) and clastic units (orange), Lochan nan Dunan, north Trotternish, Skye.



Figure 6-30: Detail of clastic sequence at base of Lochan nan Dunan section, north Trotternish, Skye. Hammer *ca*. 50 cm long.

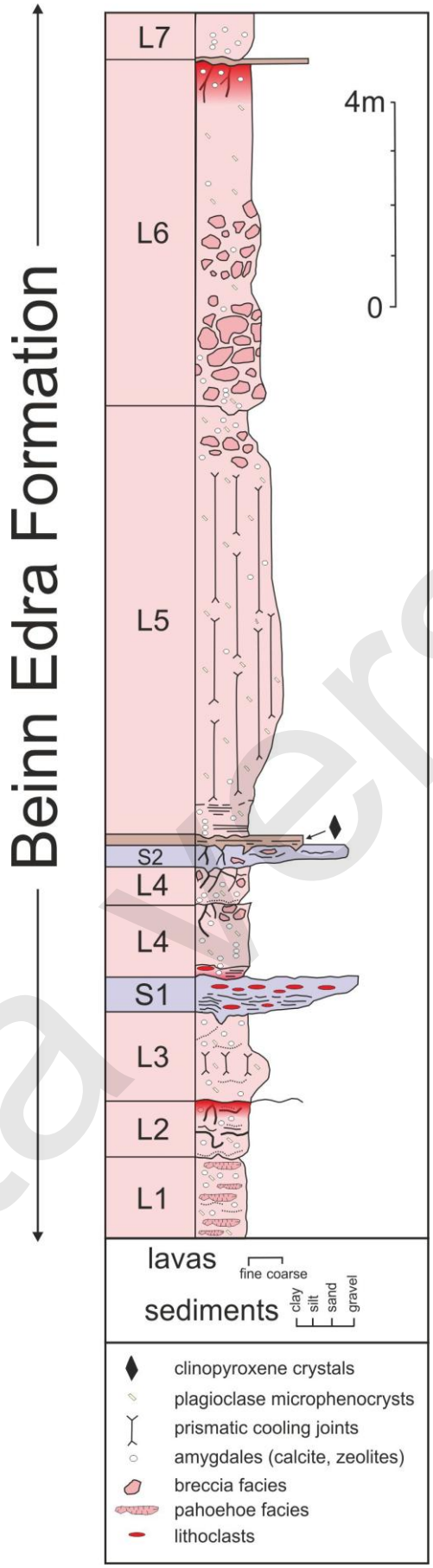


Figure 6-31: Log of sequence of basaltic lavas with weathered tops (bright red) and clastic units (orange), Lochan nan Dunan, north Trotternish.

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Figure 6-32: Sequence of conglomerates, sandstones, siltstones and thin coals, Allt Geodh a' Ghàmhna, Minginish, SW Skye.



Figure 6-33: Sandstones, siltstones and a thin coal at top of the Allt Geodh a' Ghàmhna section, Minginish, SW Skye. Coin *ca*. 24 mm across.

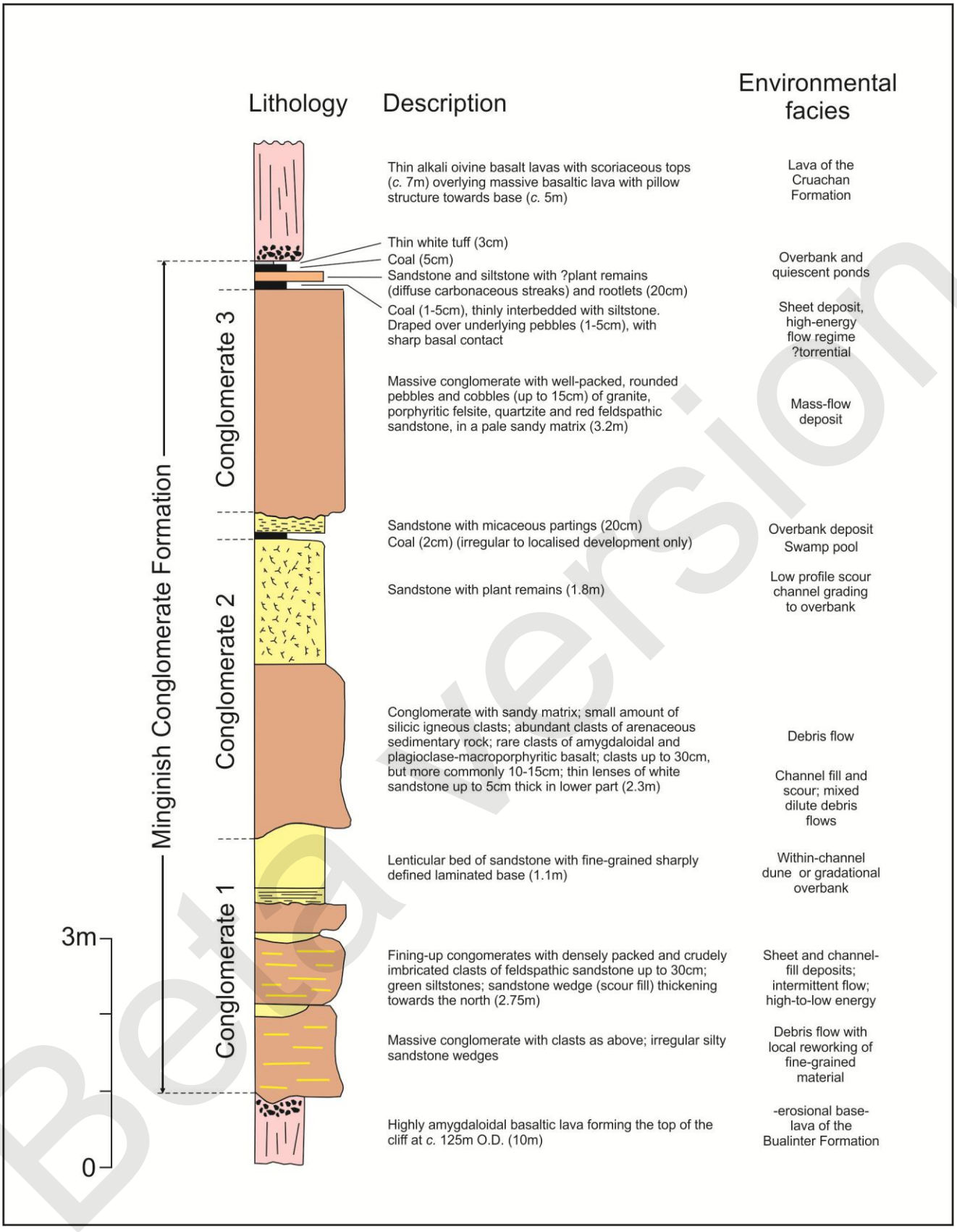


Figure 6-34: Log of sequence of conglomerates, sandstones, siltstones and thin coals, Allt Geodh a' Ghàmhna, Minginish, SW Skye.

These sedimentary sequences have been used, with varying degrees of success, to subdivide the lava fields into coherent mappable formations (Figure 6-35) (Anderson & Dunham, 1966; Emeleus, 1985, 1997;

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Williamson & Bell 1994, 2012). The lavas in the upper part of the Mull sequence and much of the Morvern sequence appear to lack sedimentary beds or other distinctive stratigraphical markers, restricting the subdivision of these lava sequences.

Lava field	Sector	Formations	Members and other notable subdivisions
Skye	North [1]	Osdale Bracadale Beinn Totaig Ramasaig Beinn Edra Portree Hyaloclastite	Glen Osdale conglomerates and siltstones Trotternish Shale
	West-central [2,3]	Talisker Preshal Beg Conglomerate Gleann Oraid Loch Dubh Eynort Mudstone Fiskavaig Glen Caladale Cruachan Minginish Conglomerate Bualintur Rubh' an Dùnain	 Sleadale, Cnoc Scarall, Arnaval Loch an Sguir Mhoir, Biod Mór, Ben Scaalan Rubha nan Clach, McFarlane's Rock Skridan, Sgurr Buidhe, Stac a'Mheadais, Tusdale Glen Brittle, An Còcan Culnamean, Allt Geodh' a'Ghàmhna, Allt Mór Creag Mhór, Meacnaish, An Leac
	North-central [3]	Fionn Choire Roineval Coire nan Circe Sligachan	 Meadale, Carbost Conglomerate, Harport Am Mam, Coire Daraich, Sron a' Ghrobain, Allt Dearg Meall Odhar, Cnoc an t-Sithean
	South-central [4]	Strathaird	Upper Lava, Picrite Basalt, Ophimottled Basalt, Basal Lava
	Canna/ Sanday [5]	Canna Lava	Eilean a'Bhàird, Beul Làma Sgorr, Carn a'Ghaill, Cnoc Bhrostan, Tighard
	NW Rum [5]	Canna Lava	Orval, Guirdil, Upper Fionchra, Lower Fionchra
Eigg	Eigg [5] Eigg [5]	Sgurr of Eigg Pitchstone Eigg Lava	 Cora-bheinn, Cnoc Creagach, Brutach Dearg, Glacan Dorchadois, Gleann Charàdail, Laig
	SE Rum [5]	Eigg Lava	undivided
	Muck [5]	Eigg Lava	Beinn Airein–an Stac, Port an t-Seilich, Basal
Mull	Mull [6]	Mull Central Lava Mull Plateau Lava Staffa Lava	Undivided Ben More Pale, Ben More Main Quinish Lava, Geochemical subdivisions [7] Ardtun Conglomerate and equivalents MacCulloch's Tree/Fingal's Cave/Carraig Mhór Flow Undivided sequence in Ross of Mull Malcolm's Point Conglomerate Gribun Mudstone and equivalents
	Ardnamurchan and Morvern [8]	Mull Plateau Lava	undivided

1 Anderson and Dunham (1966); 2 Williamson and Bell (1994); 3 British Geological Survey, 2000, Minginish, Scotland. Sheet 70, Solid and Drift Geology 1:50 000 Series; 4 Almond (1964); 5 Emeleus (1997); 6 Bailey et al. (1924); 7 Kerr (1995a,b); 8 Richey and Thomas (1930)

Figure 6-35: Paleocene lava fields of the Hebridean Igneous Province (HIP).

The conglomerates within the lava sequences may also provide provenance information for the periods during which active erosion occurred.

Beta version

Locally, thick accumulations of debris formed during construction of the lava fields (Brown *et al.* 2009), for example at Maclean's Nose, south of Ben Hiant on Ardnamurchan (Richey & Thomas, 1930; Brown & Bell 2006) (Figure 6-36), and at Compass Hill on the east side of Canna (Harker 1908; Emeleus 1997).



Figure 6-36: Poorly sorted debris flow deposits, Maclean's Nose, Ben Hiant, Ardnamurchan.

The original limits of the lava fields are not easily estimated. However, given that the coastal cliffs, up to 300 m high, which mark the onshore truncation of the lava piles on, for example Skye and Mull, taken together with the horizontal attitude and thickness of the lava piles, suggests that they extended at least 50 km beyond their present-day limits. Extensive areas of basaltic lavas are known to exist below sea level, SW of Skye and west and NW of Mull.

6.3 Petrography of the lavas

The lava fields are made up predominantly of basaltic lavas, with a lesser quantity of more evolved compositions, ranging from hawaiite and tholeiitic basaltic andesite to trachyte and rhyodacite. The general petrographical and mineralogical characteristics of lavas of the Skye and Mull fields, which have been summarised by Williamson & Bell (1994, 2012) and Bell & Williamson (2002, 2024), and those of the Small Isles by Emeleus (1985, 1997), are outlined in Figure 6-37. The geochemistry of the lavas is discussed in Chapter 10.

Beta Version

Lava type	Mineralogy and petrography
Alkali basalt and transitional olivine basalt (both commonly mapped as olivine basalt)	Phenocrysts and microphenocrysts of olivine (Fo_{87-70}), plagioclase (An_{70-55}) and rare clinopyroxene. Groundmass of plagioclase laths, commonly ophitic diopsidic augite/titanaugite ($En_{43}Fs_{14}Wo_{43}$) and minor titanomagnetite and apatite. Chrome-spinel as inclusions in olivine and rarely as microphenocrysts.
Picrobasalt	Abundant phenocrysts of olivine (Fo_{89-85}) enclose chrome-spinel. Matrix of olivine, plagioclase laths, ophitic diopsidic augite and titanomagnetite. Groundmass minerals of similar composition to alkali basalt.
Hawaiite	Phenocrysts of compositionally zoned plagioclase (An_{51-45}), olivine (Fo_{75-50}) and rarer augite ($En_{45}Fs_{10}Wo_{45}$). Abundant microphenocrysts of magnetite. Groundmass of plagioclase ($An_{60}Ab_{39}Or_{1}$-$An_{15}Ab_{80}Or_{5}$), ophitic to subophitic clinopyroxene ($En_{38}Fs_{20}Wo_{42}$), minor biotite, amphibole, apatite and interstitial alkali feldspar ($An_{2}Ab_{60}Or_{38}$). Plagioclase phenocrysts and xenocrysts up to 25mm long in 'Big Feldspar' varieties.
Mugearite	Phenocrysts of zoned olivine (Fo_{40-18}), plagioclase (An_{60-30}) and iron-rich clinopyroxene . Groundmass of flow-aligned plagioclase laths ($An_{22}Ab_{68}Or_{10}$), equigranular clinopyroxene ($En_{38}Fs_{16}Wo_{46}$), apatite needles and granular titanomagnetite, with minor Fe-rich olivine, biotite, amphibole and interstitial alkali feldspar. Uncommon 'Big feldspar' variants.
Benmoreite	Abundant microphenocrysts of flow-aligned, zoned plagioclase (andesine-oligoclase) and anorthoclase. Fine-grained groundmass of flow-aligned alkali feldspar and sodic plagioclase laths, granular clinopyroxene and magnetite, and apatite needles. Rare olivine, typically serpentinised.
Trachyte	Phenocrysts of anorthoclase or sodic sanidine ($An_{1}Ab_{48}Or_{51}$), Fe-rich clinopyroxene ($En_{21}Fs_{33}Wo_{46}$) and rare olivine (Fo_{20}) and microphenocrysts of apatite. Abundant small flow-aligned sodic alkali feldspar laths, and interstitial sodic pyroxene and amphibole.
Tholeiitic olivine basalt	Sparse microphenocrysts of zoned olivine (Fo_{91-55}) and plagioclase (An_{90-66}). Groundmass of plagioclase laths (An_{82}), clinopyroxene ($En_{43}Fs_{12}Wo_{45}$), olivine and homogeneous titanomagnetite. Minor apatite and amphibole. Calcium-poor pyroxene absent.
Tholeiitic basalt	Rare phenocrysts of plagioclase (An_{87-76}) and altered olivine. Fine-grained plagioclase laths (An_{72}), granular aggregates of augite ($En_{47}Fs_{12}Wo_{41}$), rare pigeonite and opaque oxides. Interstitial glass, commonly altered to chlorite.
Tholeiitic basaltic andesite	Phenocrysts of plagioclase ($An_{57}Ab_{41}Or_{2}$ - $An_{30}Ab_{63}Or_{7}$), augite ($En_{43}Fs_{17}Wo_{40}$), and rare orthopyroxene ($En_{65}Fs_{31}Wo_{4}$). Fine-grained groundmass of plagioclase laths ($An_{40}Ab5_{6}Or_{4}$), granular clinopyroxene ($En_{40}Fs_{23}Wo_{37}$), magnetite and interstitial glass of sodic granite composition.
Tholeiitic andesite ('Icelandite')	Phenocrysts of plagioclase ($An_{60}Ab_{39}Or_{1}$ - $An_{38}Ab_{58}Or_{4}$), augite ($En_{42}Fs_{18}Wo_{40}$), orthopyroxene ($En_{66}Fs_{30}Wo_{4}$), titanomagnetite and apatite. Very fine-grained groundmass of plagioclase laths, magnetite grains and granular pyroxene.
Rhyodacite vitrophyre ('pitchstone')	'Phenocrysts' of plagioclase ($An_{32}Ab_{60}Or_{8}$), grid-twinned anorthoclase ($An_{6}Ab_{51}Or_{43}$), clinopyroxene ($En_{44}Fs_{18}Wo_{38}$), orthopyroxene ($En_{68}Fs_{29}Wo_{3}$), magnetite, ilmenite, apatite and rare quartz. 'Phenocrysts' (especially feldspar) commonly embayed. Groundmass of flow-banded glass, commonly devitrified to dusty, felsitic groundmass.

Figure 6-37: Mineralogical and petrographical characteristics of the principal lava types in the Hebridean Igneous Province (HIP).

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6.4 Field characteristics of the lavas and sedimentary units

6.4.1 Introduction

A variety of field and hand specimen characteristics have been identified for each of the main lava rock types (e.g. Williamson & Bell 1994, 2012; Emeleus 1997; Bell & Williamson 2002, 2024) and these generally permit field identification and interpretation without immediate recourse to microscopic examination. Any stratigraphic terms used below are detailed in Section 6.5, below, and are included here merely to provide orientation.

6.4.2 Flow types: simple and compound

Two main types of lava architecture are recognised – simple and compound - albeit with a degree of transition (Figure 6-38; Figure 6-39; Figure 6-40; Figure 6-41) (Walker 1993).



Figure 6-38: Simple lavas, with lower prismatic colonnades and (upper) dark rubbly tops, dominating the sequence at the top of the cliff section at Malcolm's Point, Brolass, SW Mull.

Pre-submission

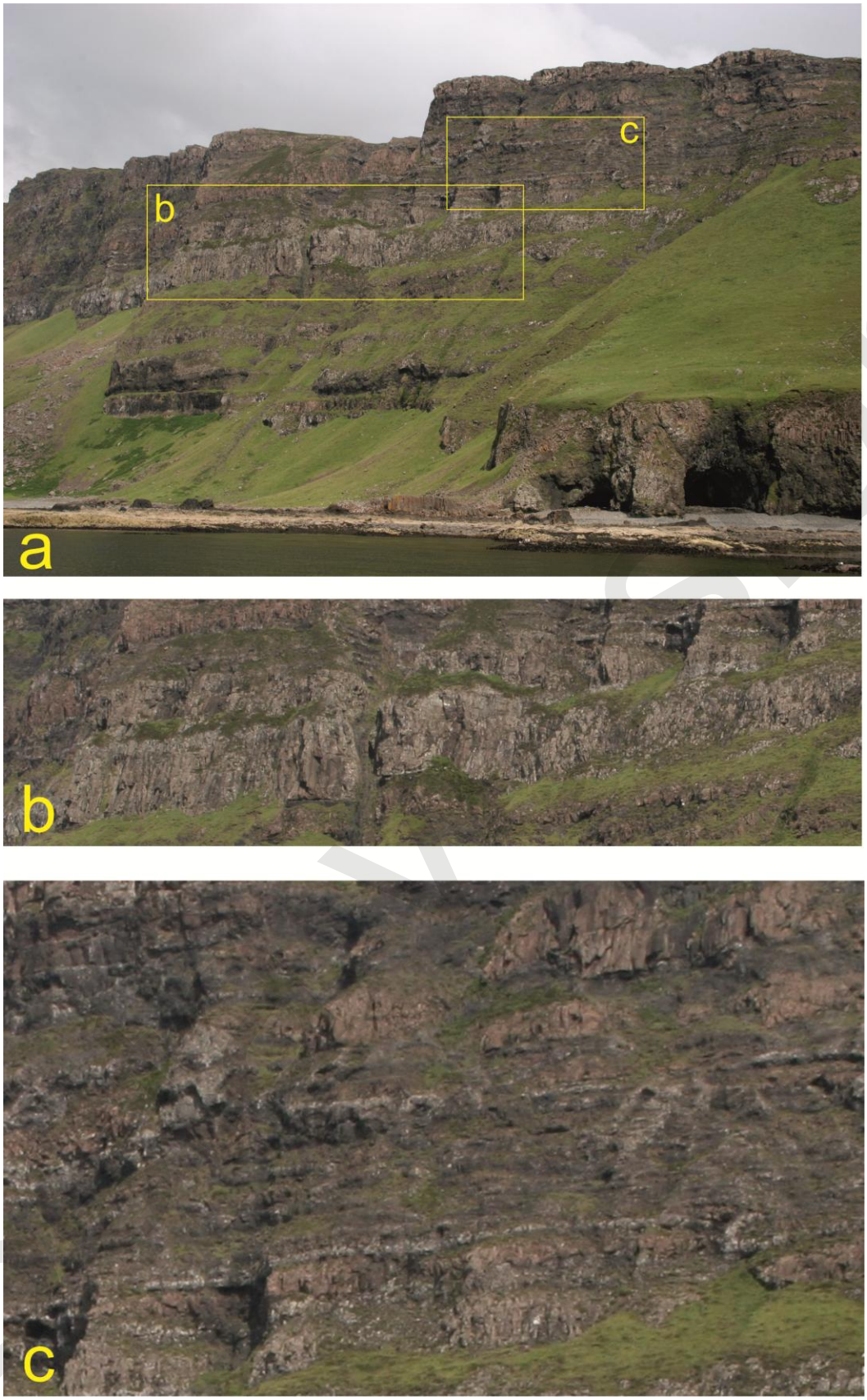


Figure 6-39: Examples of simple (columnar-jointed) (b) and compound (c) lavas within the west facing cliffs (a) of Ardmeanach, SW Mull.

Br



Figure 6-40: Compound lavas overlying prismatic-jointed lavas, Eigg Lava Formation, Sgòrr an Fhàrraidh, Eigg.

Beta version

As the term implies, a simple lava is the product of a single eruption (or 'emplacement') event, commonly within the HIP (but not always) with a lower columnar- or prismatic-jointed part and an upper more brecciated/rubbly portion (Figure 6-38; Figure 6-41). Such lavas have also been described as 'tabular-classic'. Thicknesses are commonly greater than 6 m. These relatively high aspect ratio lavas (thickness:lateral extent, > 0.05?) are common for basaltic lavas and typical (but not exclusively) of more evolved composition (hawaiite, mugearite etc.).



Figure 6-41: Detail of simple lavas, with lower prismatic colonnades and (upper) dark rubbly tops, dominating the sequence at the top of the cliff section at Malcolm's Point, Brolass, SW Mull.

Compound lavas are, in contrast, the result of multiple events during a more protracted eruption, commonly involving auto intrusion of lava lobes (or pahoehoe lobes, see below), whereby subsequent pulses of magma of an eruption invade or intrude early erupted material, causing the overall thickness of the lava to increase (Figure 6-42; Figure 6-43). The front of the lava advances in a piecemeal fashion as a myriad of lobes, rather than a single more coherent sheet. Such lavas have also been described as 'compound braided'.

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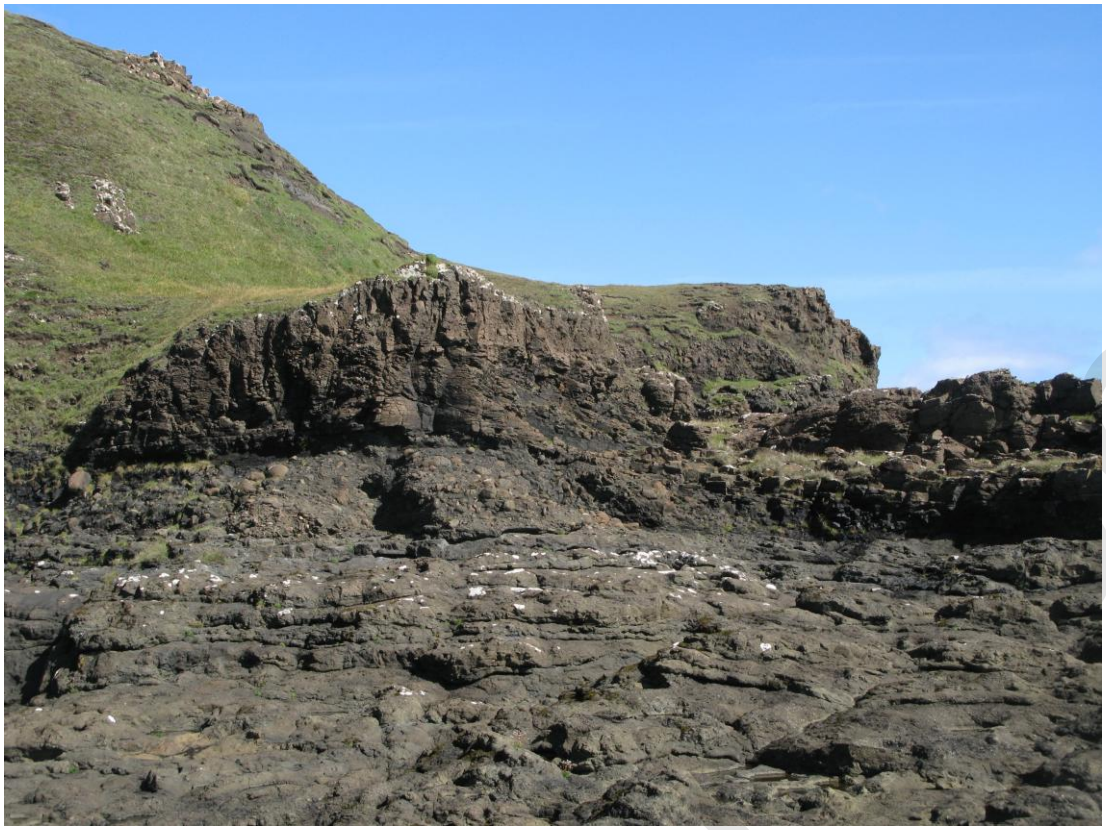


Figure 6-42: Example of a compound lava, with multiple, thin lobes (near ground), overlain by a boulder conglomerate bed. Tallabric, south Sanday.



Figure 6-43: Detail of a compound lava, with multiple, thin lobes. Tallabric, Sanday. Ruler 30 cm long.

Two morphological terms commonly used to describe basaltic lavas are pahoehoe ('smooth surfaced') and a'a ('rough surfaced') (Figure 6-44). Volumetric flow rate is an important factor in determining which form dominates: higher flow rates favour a'a lavas, advancing within open channels wherein there is no inflation, and the upper fragmented facies is the product of 'auto brecciation'. This brecciation or fragmentation does not repair and results in a surface layer of spinose, clinker rubble fragments. Below this fragmental carapace, the lava is relatively coherent. Flow thickness increases with distance from vent, with initially (close to vent) deformed vesicles eliminated with increasing distance from vent.



Figure 6-44: Brecciated top of a simple basaltic lava, south of Quinish Point, NW Mull. Pole ca. 1 m long.

Compound lavas commonly, but not always, have pahoehoe characteristics and the term compound pahoehoe lava is frequently used. Smooth, billowy and crenulated surfaces are common, but preservation potential is commonly poor (Figure 6-45; Figure 6-46). These lavas advance due to auto-intrusion, which preserves heat and retards the crystallisation of magma. Flow front advancement is, by comparison to simple flows, relatively (but not always) slow. A variety of pahoehoe types are recognised, based on surface texture and internal characteristics.



Figure 6-45: Remnant of a crenulated pahoehoe-like lava surface, south of Quinish Point, NW Mull. Pole *ca.* 1m long.



Figure 6-46: Remnant of a crenulated pahoehoe-like lava surface, Carraig Mhòr, Brolass, SW Mull. Pole *ca.* 1m long.

Flows can transition between a'a and pahoehoe (Figure 6-47). Major controlling factors are viscosity, which increases during cooling of magma, and strain rate, which essentially is rate of flow and is typically influenced by the slope of the surface over which the lava migrates. Degassing of lavas, producing vesicles (ultimately amygdales if filled by hydrothermal minerals during burial), promotes crystallisation.



Figure 6-47: Partially brecciated weathered top of a lava with pahoehoe surfaces, Port Mòr, SE Muck. Lens cap *ca*. 8 cm across.

The joint patterns in lavas are a product of volume reduction of magma during crystallisation and stress release at sub-magmatic temperatures. A lava is referred to as being columnar-jointed if the columns are perfectly (or near perfectly) hexagonal, having developed orthogonal to the cooling surface: vertical on a horizontal land surface, horizontal against, for example, a vertical valley wall (Figure 6-48; Figure 6-49). Less perfect joints are referred to as being prismatic (Figure 6-50).

Beta



Figure 6-48: A classic simple lava with lower, columnar-jointed colonnade and an upper, wavy-jointed entablature. Lozenge-shaped, jointed masses within the entablature (top of cliff section) are most likely invasive lobes, emplaced as part of the same eruption. Staffa, Inner Hebrides. Height of cliff is 42 m. Person for scale.



Figure 6-49: Detail of the columnar-jointed colonnade of the Fingal's Cave Lava, Staffa, Inner Hebrides.

Borrow



Figure 6-50: Simple (prismatic-jointed) lavas within the SW facing cliffs of Beinn Iadain, Morvern. View towards Ben Hiant, Ardnamurchan, and Rum.

In many columnar-jointed lavas, the upper portion comprises more complex, 'wavy' joints. In such lavas, the lower more perfectly jointed portion is referred to as the colonnade and the upper complex portion as the entablature (Figure 6-51). Commonly there is a remarkably sharp boundary between the two joint facies (Figure 6-52). Columnar-jointed lavas commonly develop when a simple flow (partially) infills valleys with active drainage systems (Figure 6-53). The joint distribution pattern is interpreted as the product of the lower portion of the lava, once it has stopped flowing, losing heat through its floor, commonly on a wet substrate, producing the colonnade, whilst the upper portion, the entablature, results when water ingresses the top of the lava, typically when the drainage system is re-established.

Beta version



Figure 6-51: Classic columnar-jointed colonnade and entablature of the Fingal's Cave Lava, Staffa. Height of cliff is 42 m.



Figure 6-52: Sharp demarcation between columnar-jointed colonnade (lower) and wavy-jointed entablature (upper) of the Fingal's Cave Lava, Staffa.



Figure 6-53: The two outliers of the Preshal More intra-canyon basaltic lava, forming the peaks of Preshal More (near) and Preshal Beg (far), giving rise to an inverted topography due to their resistance to erosion.

There are many good examples of simple lava flows throughout the HIP, with their attendant joint patterns (Figure 6-54; Figure 6-55; Figure 6-56; Figure 6-57; Figure 6-58; Figure 6-59; Figure 6-60).



Figure 6-54: Remnant of a prismatic-jointed basaltic lava capping a simple basaltic lava with colonnade, entablature and rubbly top, Codh' an Dùnain, Brolass, SW Mull.

Pre-version

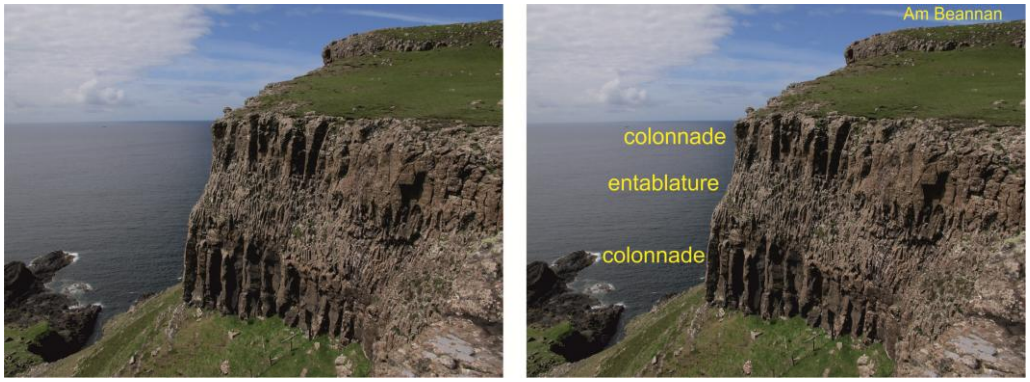


Figure 6-55: A (double)-tiered simple basaltic lava, with upper and lower colonnades (well-developed prismatic columns) and a central entablature (complex wavy columns), Brè-sgorr, SW Canna.

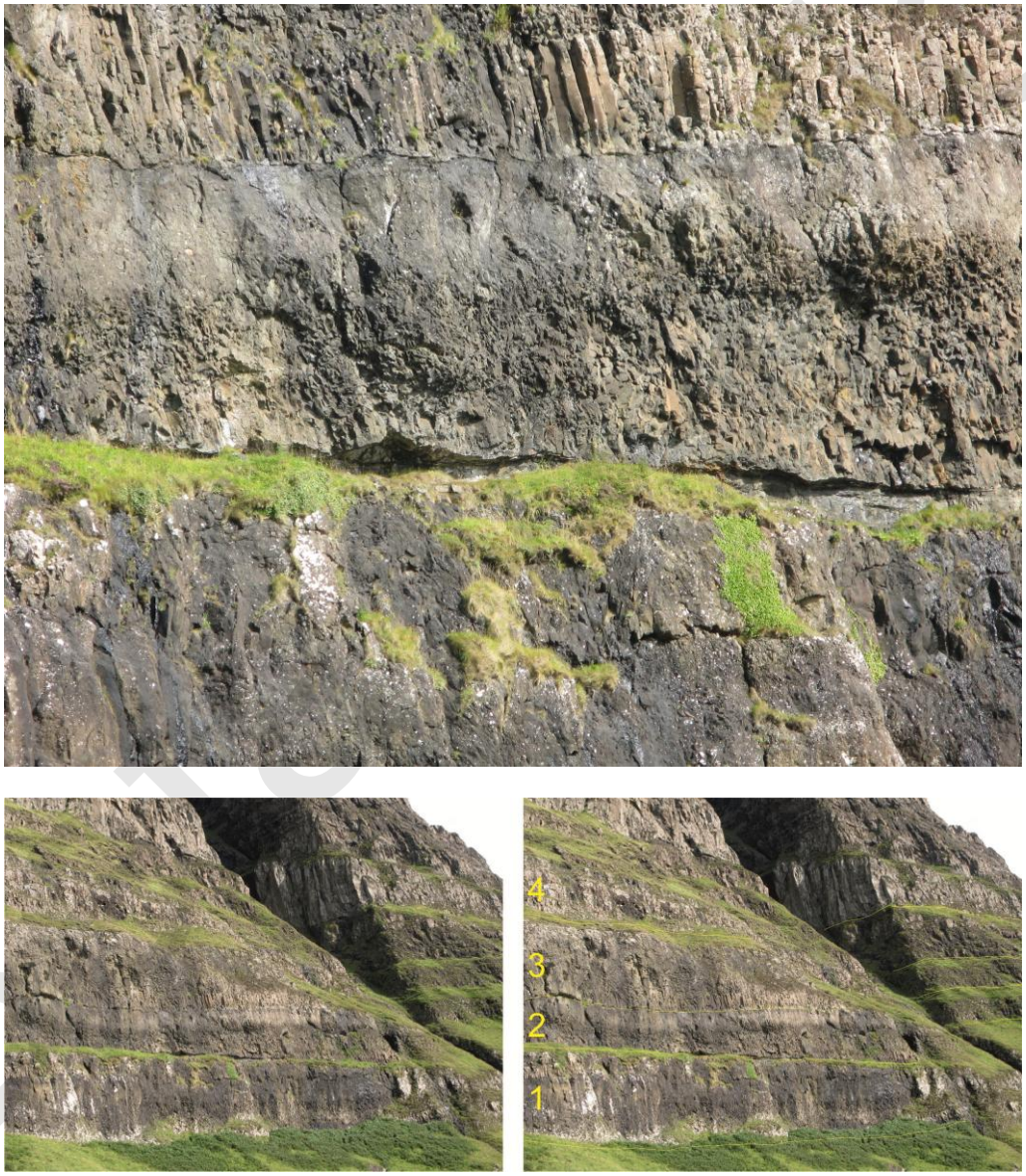


Figure 6-56: Examples of simple, prismatic-jointed lavas (numbered) within the west facing cliffs of Ardmeanach, north of Macculloch's Tree, SW Mull.

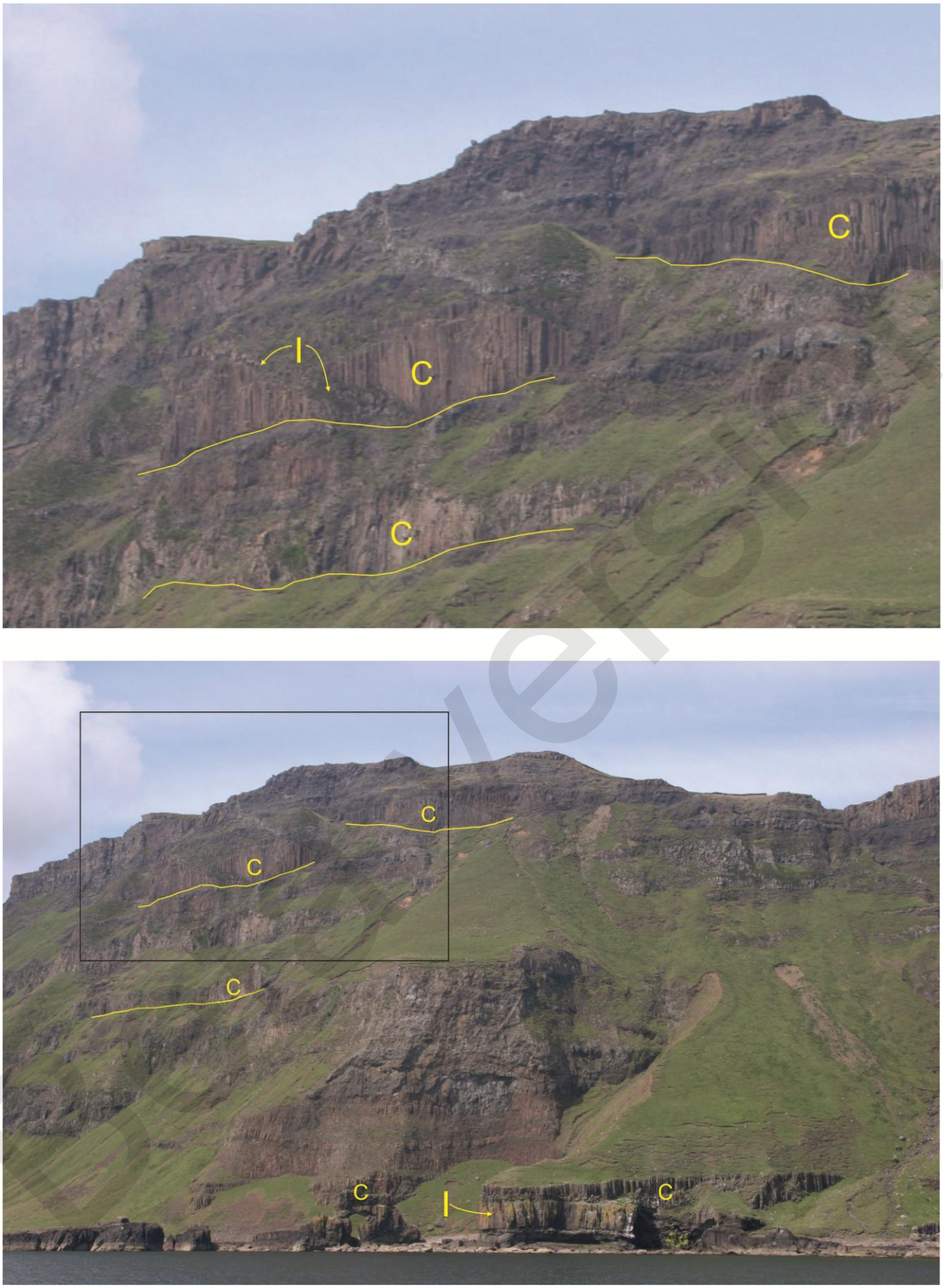


Figure 6-57: Examples of simple, prismatic-jointed lavas within the cliff section at Malcolm's Point, Brolass, SW Mull. Base of each lava and its attendant colonnade (C) indicated. I, unrelated minor intrusion.



Figure 6-58: Examples of simple, prismatic-jointed basaltic lavas with reddened (weathered) tops, Oronsay, Loch Bracadale, south Duirinish, Skye. Height of cliff *ca*. 70 m.



Figure 6-59: Examples of simple, prismatic-jointed lavas with reddened (weathered) tops, Idrigill Point, south Duirinish, Skye. Height of cliff *ca*. 50 m.



Figure 6-60: Weakly developed prismatic joints in a simple basaltic lava overlying the Port Mòr tuff (bright red), SE Muck.

Some simple lavas, which are interpreted to been impounded in a topographic low of the volcanic landscape, for example a river channel, have a more complex make-up, for example having an upper and/or lower pillow facies, indicative of interaction with water (Figure 6-61; Figure 6-62).

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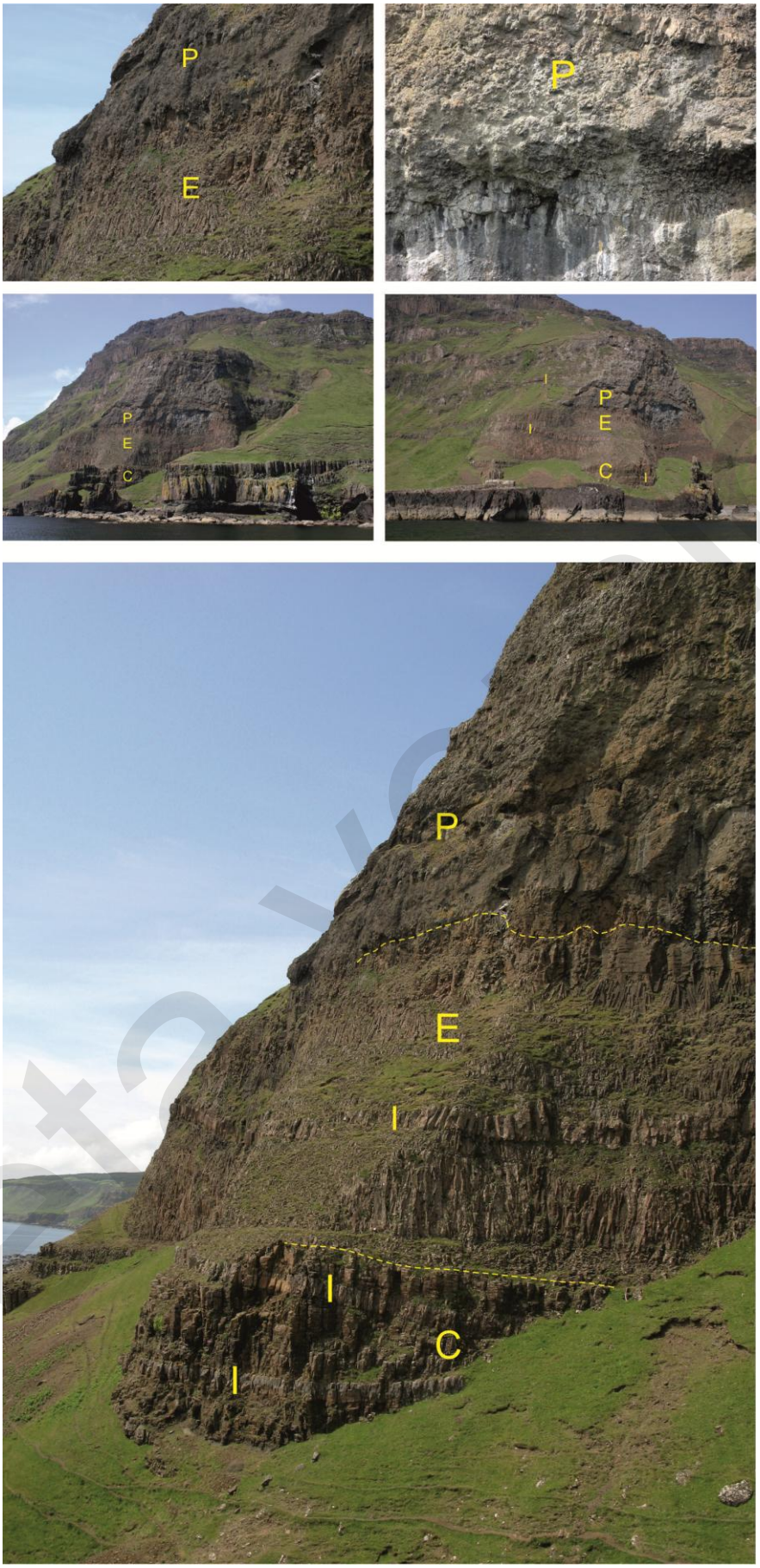


Figure 6-61: Thick (impounded?) simple basaltic lava with colonnade (C), entablature (E) and upper pillow and breccia (P) facies. Malcolm's Point, SW Mull. I, unrelated minor intrusions.

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Figure 6-62: Upper part of thick (impounded?) simple basaltic lava with wavy-jointed (entablature) and overlying pillow and breccia facies. Malcolm's Point, SW Mull. Entablature is cut by a prominent unrelated minor intrusion.

The internal details of compound lavas are well illustrated throughout the HIP (Figure 6-63; Figure 6-64; Figure 6-65; Figure 6-66; Figure 6-67).

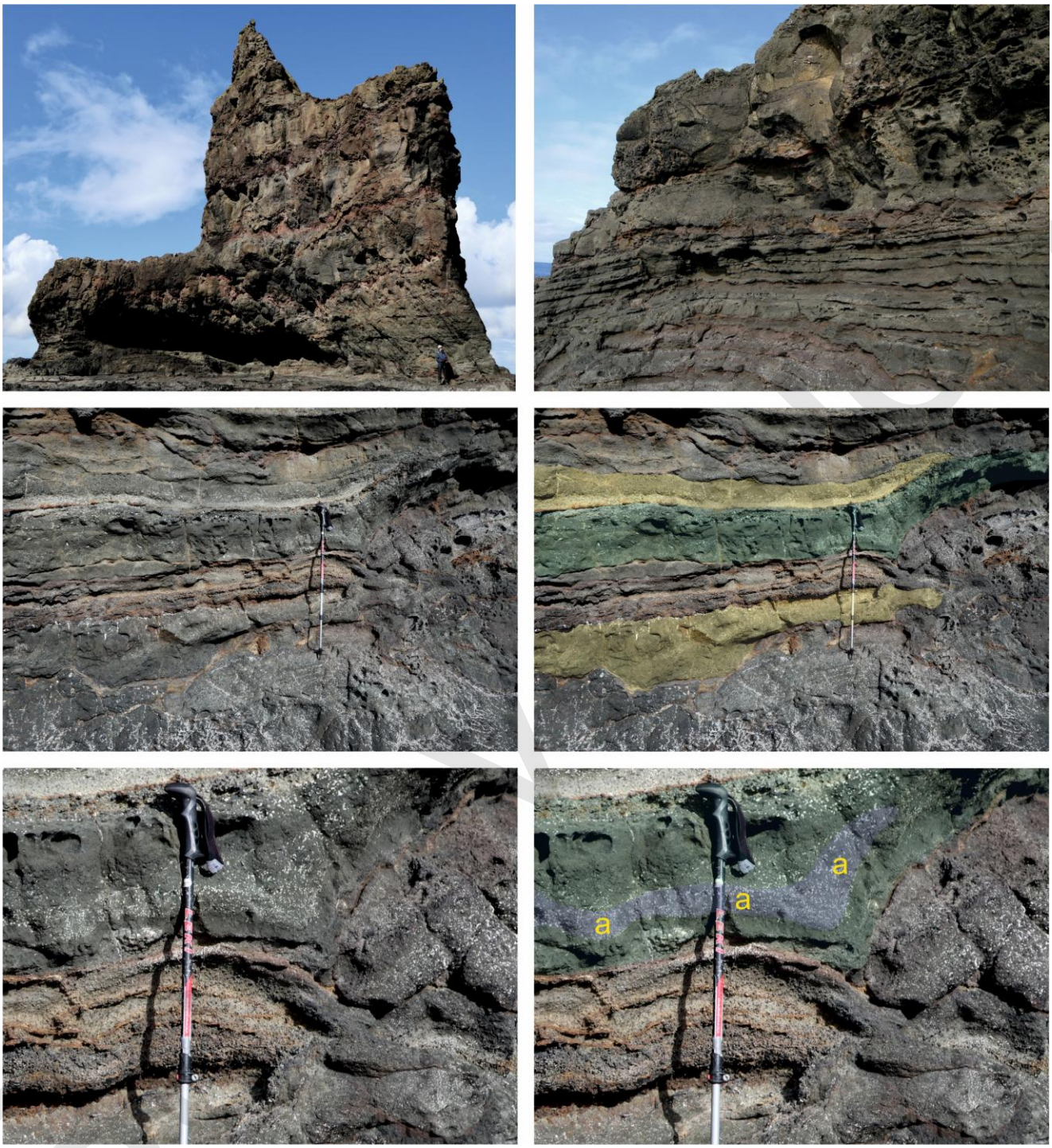


Figure 6-63: Compound lava forming the tidal pillar of An Stac, south side of Talisker Bay, Minginish, SW Skye. Different (false, added) colours identify individual lobes of the lava. a, amygdale-rich core of a lobe. Pole *ca.* 1 m long.

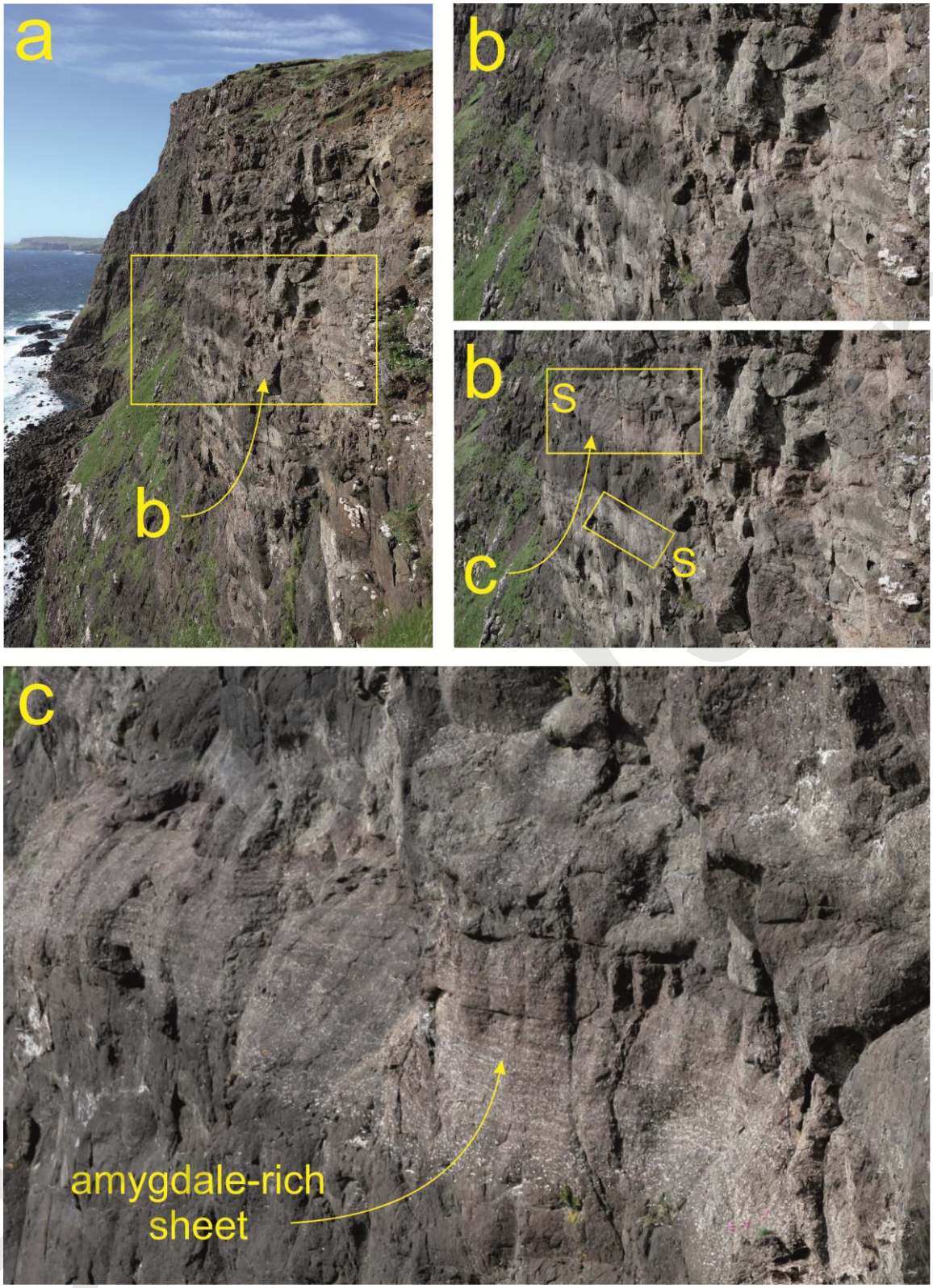


Figure 6-64: Compound basaltic lava with amygdale-rich (v) sheets within the Ramasaig Cliff, Duirinish, west Skye. Height of cliff *ca*. 200m.



Figure 6-65: Compound lava overlain by an unstratified conglomerate, overlain by a weakly-jointed simple flow. Cormorant Cave, Tallabric, Sanday.

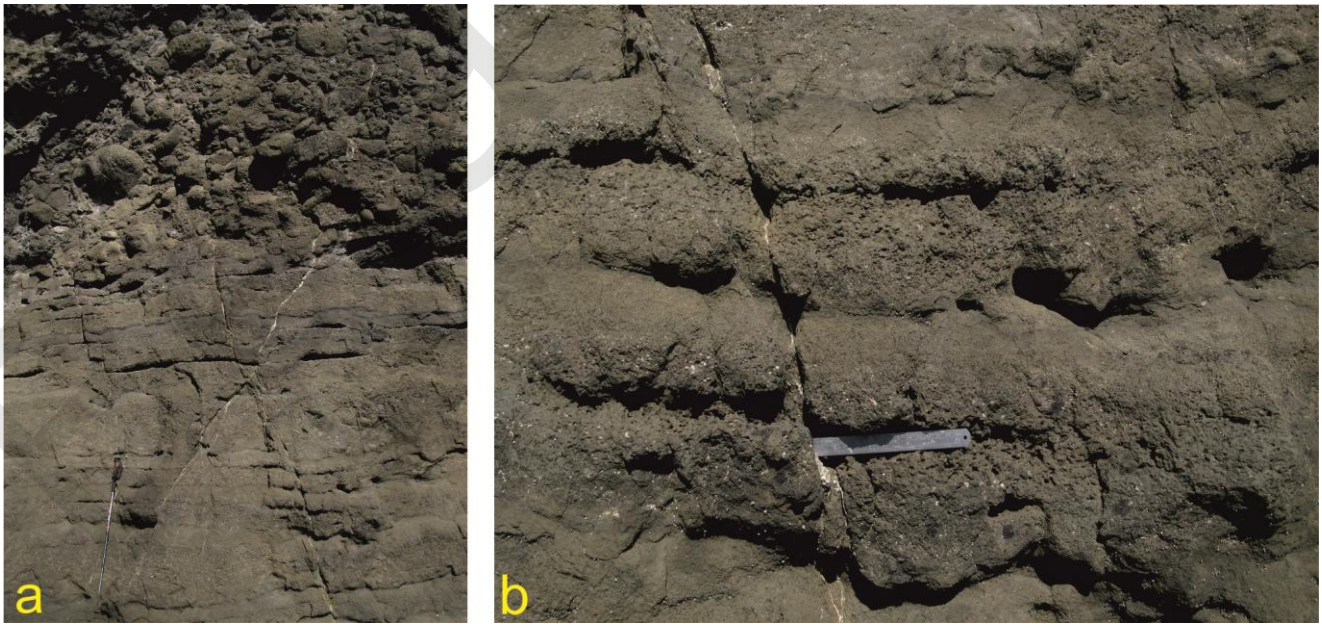


Figure 6-66: (a) Compound basaltic lava, with differentially weathering lobes, overlain by an unstratified conglomerate, Cormorant Cave, Tallabric, Sanday, pole *ca*. 1 m long; and, (b) detail of (a), ruler 15 cm long.

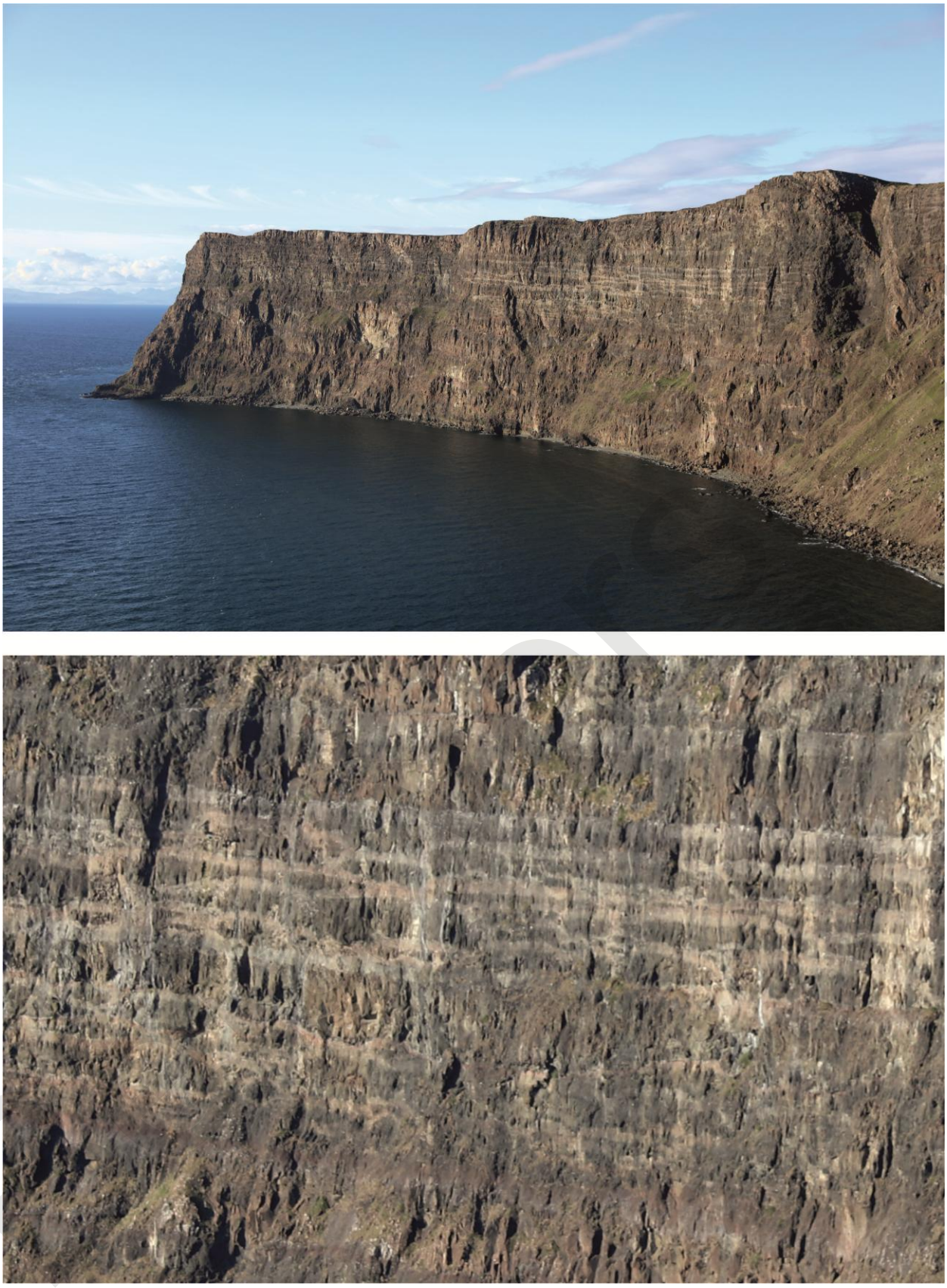


Figure 6-67: Compound basaltic lava with prismatic-jointed lobes, Biod Bàn, north Oisgill Bay, Duirinish, west Skye. Height of cliff *ca.* 170 m.

Many coastal cliff sections comprise complex interbedded simple and compound lavas (Figure 6-68; Figure 6-69; Figure 6-70).



Figure 6-68: Complex sequence of interbedded simple and compound lavas capped by a prismatic-jointed simple lava, A' Chuagach, Cleadale cliffs, west Eigg. Height of cliff *ca*. 150 m.



Figure 6-69: Complex sequence of interbedded simple and compound lavas, Beinn Airein, south Muck. Height of cliff *ca*. 100 m.

Proofversion



Figure 6-70: Complex sequence dominated by compound basaltic lavas, The Storr, Trotternish, north Skye. Height of cliff *ca*. 200 m.

Many inland outcrops lack good exposure, with only the central portions of lavas imperfectly visible (Figure 6-71).



Figure 6-71: Inland terraced crags of Aoineadh Beag, Morvern, defined by a complex horizontal sequence of imperfectly exposed basaltic lavas.

6.4.3 Flow characteristics

Flow characteristics are also controlled by magma viscosity (and yield strength), which increase with increasing silica content and gas content, and which strongly influence explosivity. At its simplest, low silica – low gas content magmas (typically basaltic) are effusive and relatively non-explosive, whereas high-silica – high gas content magmas (for example, trachytic) are relatively explosive. However, factors such as topography of the lava field and eruption rate/flux will influence lava morphology, for example the restriction of lavas within channels.

Eruption of lavas and pyroclastic deposits is considered to have been predominantly from fissures, now represented by the regional dyke swarms (Chapter 7), with point sources along their length leading to overlapping lavas forming during single (sustained) eruption events. These are the so-called ‘curtain of fire’ eruptions. With time, eruption tends to become restricted to fewer locations along fissures. Depending upon the extent of explosivity, fragmentation can lead to the development of spatter and scoria, typically and characteristically common close to the site/point of eruption (Figure 6-72; Figure 6-73; Figure 6-74). The initially fragmental (‘clastogenic’) nature of many basaltic eruptions is temporary and is followed by coalescence of material and normal flow.

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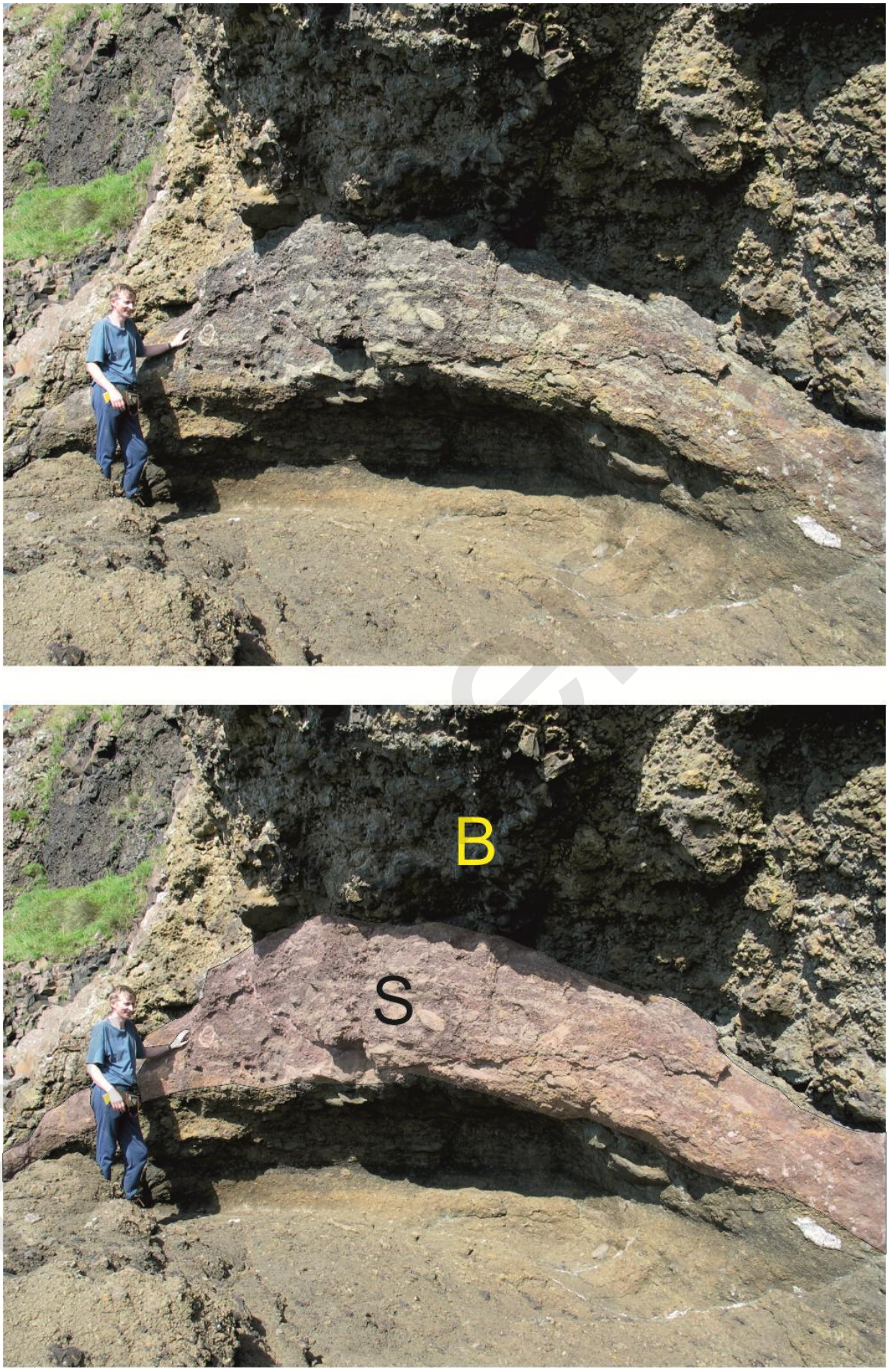


Figure 6-72: Spatter mound below the Macculloch's Tree Lava, Ardmeanach, SW Mull. S, spatter; B, base of Macculloch's Tree Lava. John Faithfull for scale.



Figure 6-73: Lava rags within basaltic lapilli tuff, below the Macculloch's Tree Lava, Ardmeanach, SW Mull. Compass *ca*. 10 cm long.



Figure 6-74: Lava rags (arrowed) within basaltic lapilli tuff, east of Malcolm's Point, Brolass, SW Mull. Pencil *ca*. 12 cm long.

Top surfaces of lavas cover a spectrum of morphologies, from thoroughly brecciated types (Figure 6-75), through to pahoehoe lavas with smooth surfaces, some with delicate (flow) crenulations preserved (Figure 6-76). Pahoehoe lavas advance at a slower rate, with progression by multiple invasive lobes, akin to finger- or ribbon-like geometries. These subsurface lava tubes facilitate low heat loss and, consequently, significant (kilometres) flow lengths. As these injection events increase, the top surface of the flow will rise (inflate). Topography also plays an important role in the development of pahoehoe flows. Low gradients enable the invasive nature of flow advancement to persist, whereas on steep slopes (greater than 5°?), residence duration is short and highly vesicular. Pipe vesicles (ultimately amygdales) are more likely to form and be preserved in flows on steeper slopes.

Pillow(ed) lavas are typical of eruption into water and are essentially compound in character (Figure 6-77; Figure 6-78; Figure 6-79). The pillows are, in 3D, commonly (but not always) connected, essentially equivalent in size and shape to pahoehoe flow units, albeit narrower. Where simple ('sheet') lavas enter water, pillowed basal facies and/or tops will develop, whether it be a static body of water such as a lake, or a river channel. The coherent cores to such flows, protected from interaction with water, commonly have prismatic joint sets. Fragmentation of these flow lobes on steep slopes (20° or more?) will yield discrete pillows that will accumulate in topographic lows. Pillows typically have glassy rims and pipe amygdales (see below) are common.



Figure 6-75: Weathered, brecciated top of basaltic lava with invasive (prismatic-jointed) lobes, Idrigill Point, south Duirinish, west Skye.

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Figure 6-76: Crenulated top surface of a basaltic lava, Carraig Mhòr, south Brolass, SW Mull. Pole *ca.*1 m long.

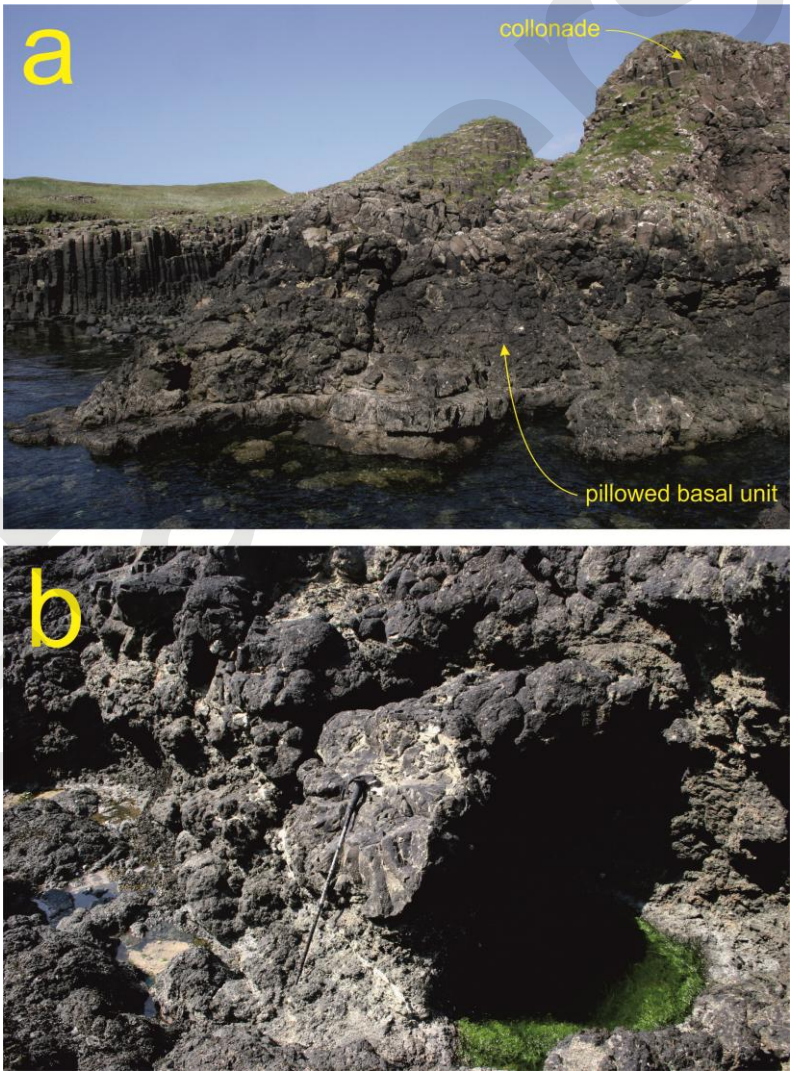


Figure 6-77: (a) Localised pillowed basal unit and overlying colonnade of Fingal's Cave Lava, Port an Fhasgaidh, Staffa; and, (b) detail of pillowed lava, pole *ca.* 1 m long.

Better version

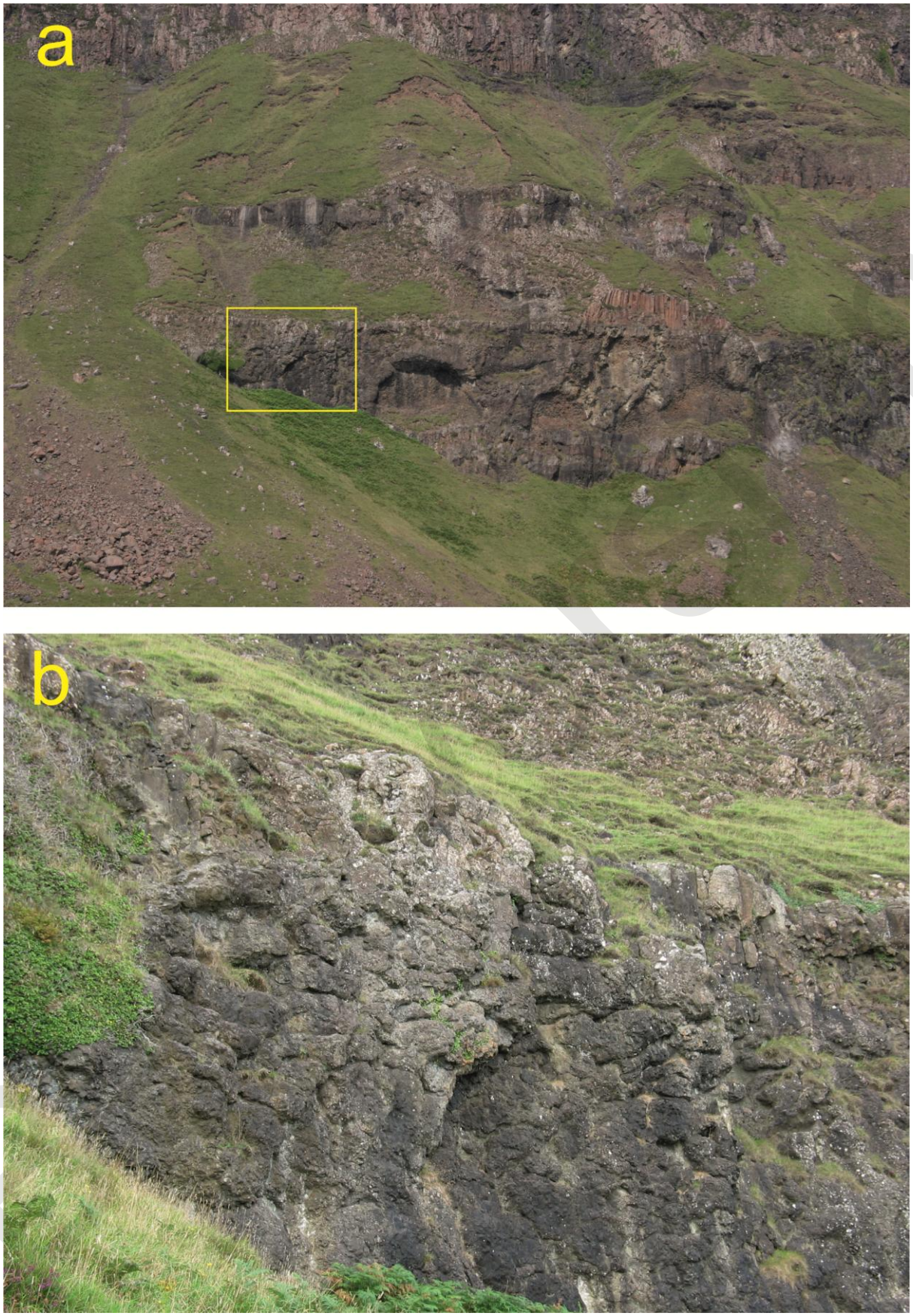


Figure 6-78: (a) Pillowed top of simple basaltic lava, Malcolm's Point cliffs, Brolass, SW Mull; and, (b) detail of area outlined in (a).

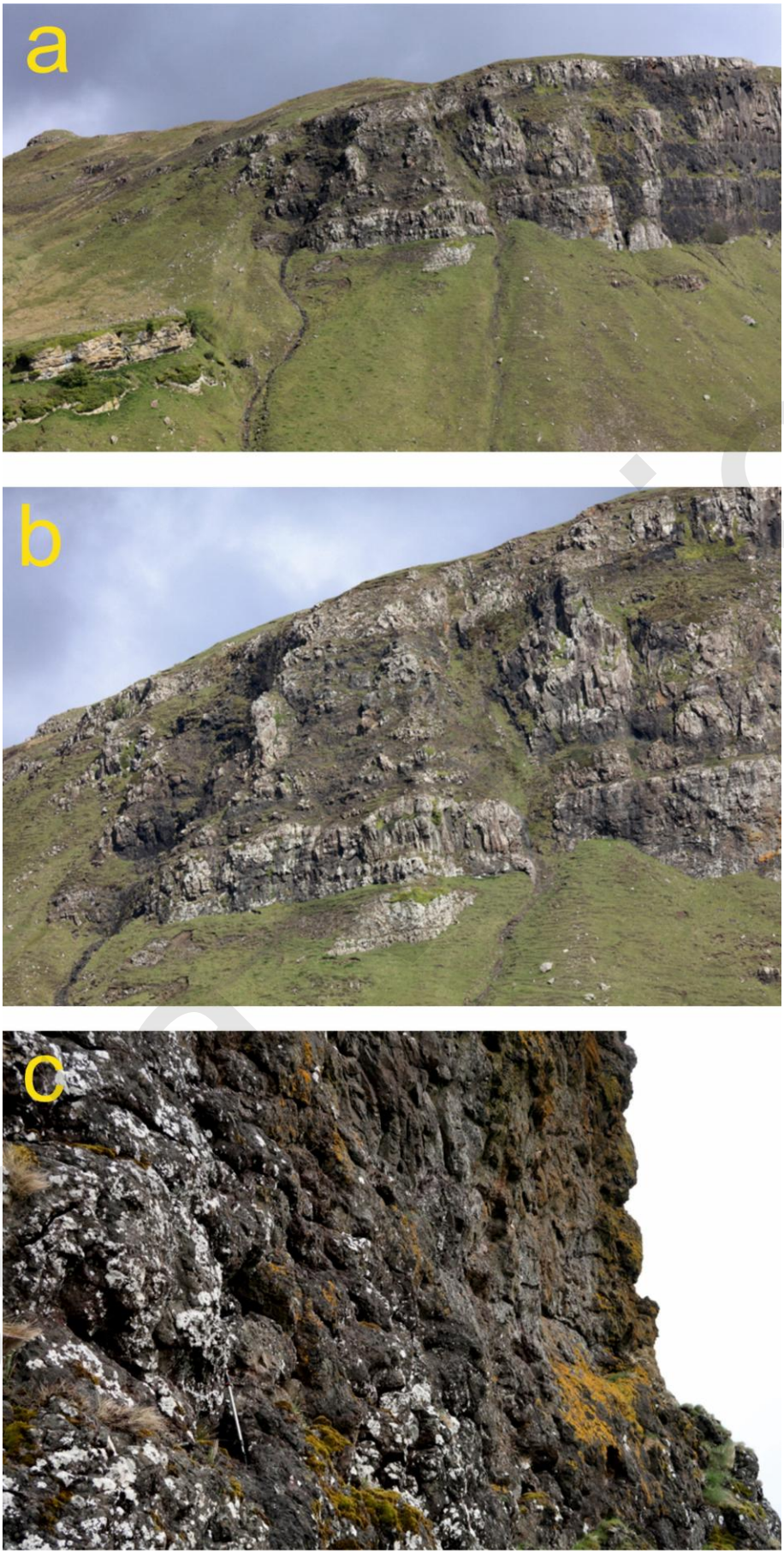


Figure 6-79: Beinn Edra Formation volcanic sequence, Creag Mhòr, north of Portree, Trotternish, Skye, comprising simple and compound subaerial lavas, with rare pillowed basaltic lava (c). Pole *ca*. 1 m long.

Hyaloclastite (or 'hyaloclastic lava') is characteristic of eruption into water (Figure 6-80; Figure 6-81; Figure 6-82; Figure 6-83; Figure 6-84; Figure 6-85; Figure 6-86). In some respects, it is akin to a'a lava, with a fragmental carapace and a coherent core. Hyaloclatite formation is most efficient where (typically basaltic) lavas enter water along coastlines, facilitating interaction with water, rapid heat loss and fragmentation. Fragmentation – quenching and granulation - is enhanced by rapid cooling due to rapid heat loss to the water, also resulting in the formation of abundant glass, subsequently transformed into palagonite, a complex, typically orange, ultra fine-grained material composed of clay and zeolites. Palagonite formation is a rapid process: in fine-grained pyroclastic deposits, complete transformation of glassy material to palagonite can be complete within a few years.



Figure 6-80: Basaltic hyaloclastite, comprising a wide range of fragment sizes, Portree Hyaloclastite Formation, Craig Ulatota, south Trotternish, Skye. Pole *ca*. 1 m long.



Figure 6-81: Basaltic hyaloclastite, comprising a wide range of fragment sizes, including radially-oriented, jointed pillows (e.g. left of centre) Portree Hyaloclastite Formation, Craig Ulatota, south Trotternish, Skye. Ruler 30 cm long.

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Figure 6-82: Detail of basaltic hyaloclastite, with discrete pillows, Portree Hyaloclastite Formation, Craig Ulatota, south Trotternish, Skye. Ruler 30 cm long.



Figure 6-83: Zeolite-cemented basaltic hyaloclastite, Portree Hyaloclastite Formation, Craig Ulatota, south Trotternish, Skye. Ruler 30 cm long.



Figure 6-84: Zeolite-cemented basaltic hyaloclastite, Portree Hyaloclastite Formation, Craig Ulatota, south Trotternish, Skye. Lens cap *ca*. 8 cm across.



Figure 6-85: Thoroughly altered basaltic hyaloclastite with large fragments of fossil wood, Macculloch's Tree site, south of Rubhan a h-Uamha, Ardmeanach, SW Mull. Compass *ca*. 8 cm long.



Figure 6-86: Basal hyaloclastite of the rhyodacite lava-like ignimbrite, An Sgùrr, south Eigg. Pole *ca.* 1 m long.

6.4.4 Flow thickness and extent

Typically, the compositionally primitive lavas have the greatest area:thickness ratio. Alkali olivine basalt and transitional olivine basalt lavas, with or without olivine phenocrysts, are characteristically less than 5 m thick, and commonly less than 2 m, typically with lateral extents of 100s of metres. Aggregates of thin units are most likely to be the product of a single, sustained eruption.

Where exposed in cliff sections, it is evident that lavas interdigitate and are not in any simple way laterally extensive. The 3D morphology of each lava is typically more ribbon-like due to the construction of lava channels controlled by the topography of the lava field as it aggrades (Figure 6-87; Figure 6-88; Figure 6-89; Figure 6-90; Figure 6-91; Figure 6-92; Figure 6-93; Figure 6-94).

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Figure 6-87: Lava section, Treshnish Point, NW Mull.



Figure 6-88: Lava section, south Ardmeanach, SW Mull.

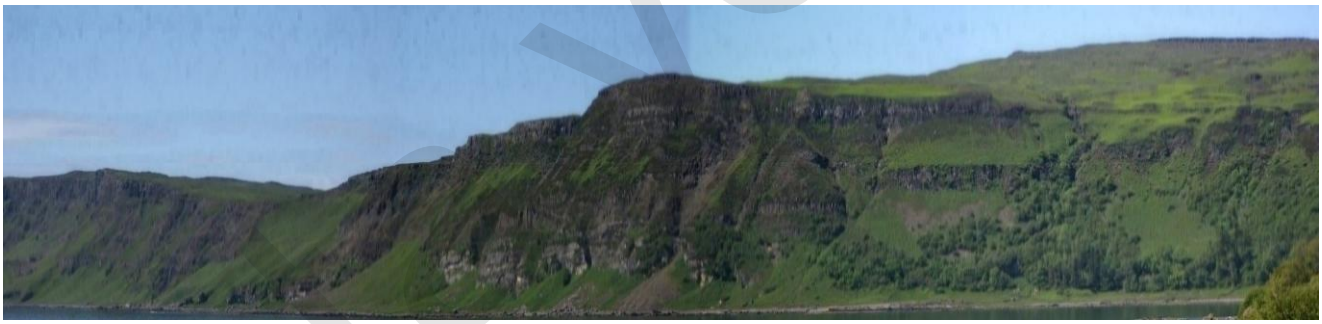


Figure 6-89: Lava section, east of Carsaig, Brollass, SW Mull.



Figure 6-90: Lava section, Lunga, Treshnish Isles.

Beta version



Figure 6-91: Lava section, Gribun, west Mull.



Figure 6-92: Lava section, Arnaval, Gleann Oraid, west-central Skye.



Figure 6-93: Lava section, south Gleann Oraid, Minginish, west-central Skye, with the inverted topography of the intra-canyon Talisker Lava forming the high ground of Preshal More.

Beta version



Figure 6-94: The cliff exposures of Ramasaig Group lavas at Waterstein Head, Duirinish, are an excellent example of the complexity of the 2D (and consequently the 3D) architecture of the HIP lava fields.

Lavas of more evolved composition, such as hawaiite and mugearite, typically have a greater volume and are commonly 8 to 12 m thick, with some greater than 20 m (Figure 6-95). They have remarkable lateral persistence, despite being derived from more viscous magmas. For example, the extents of two mugearites in northern and eastern Eigg are *ca.* 12 km in length. The unusual thickness (relative to area covered) of these far-travelled lavas suggests high effusion rates. The relatively rare benmoreite and trachyte flows are typically thick. In west-central Skye, the benmoreite of Cnoc Dubh Heilla is at least 30 m thick, and the trachyte of Cnoc Scarall in Glen Eynort is more than 100 m thick (Figure 6-96; Figure 6-97). It is, however, possible that the thickness of the latter has been accentuated through ponding.

Beta version



Figure 6-95: Mugearite lava, SW Wiay, Loch Bracadale, west-central Skye.



Figure 6-96: Benmoreite lava, Cnoc Glas Heilla, Portnalong, Minginish, west-central Skye.



Figure 6-97: Trachyte lava, Cnoc Scarall, Glen Eynort, Minginish, west-central Skye.

Evidence of flow termination is not common; rare examples include the flow fronts observed on Muck, near Torr nam Fitheach and Port an t-Seilich, and on Canna at Cùil a' Bhainne.

Beta version

6.4.5 Amygdaloid structures

Amygdales of (secondary) hydrothermal minerals are almost ubiquitous, but are best developed within the thinner, more vesiculated, unevolved lava types, such as the alkali olivine basalts (Figure 6-98; Figure 6-99). Amygdale minerals include: calcite, quartz, analcime, and the zeolites chabazite, stilbite, mesolite, thomsonite, gyrolite and apophyllite (Figure 6-100; Figure 6-101; Figure 6-102; Figure 6-103). These lavas generally have well developed basal flow structures and less common pipe amygdales; the latter are especially concentrated where the flow has over-ridden thin palaeosols and mudstones.



Figure 6-98: Bands of amygdales within a compound lava lobe, Ramasaig Cliff, Moonen Bay, Duirinish, Skye.



Figure 6-99: Amygdaloidal top of a basaltic lava, Trotternish, Skye. Hammer *ca.* 30 cm long.

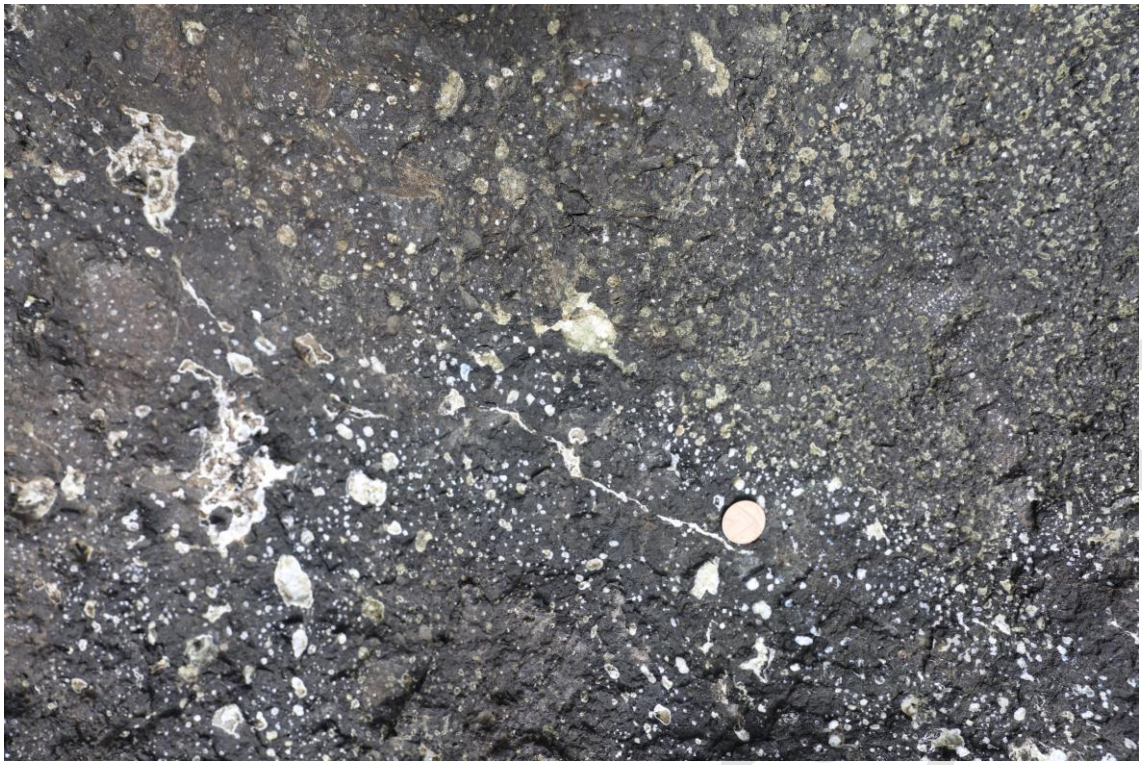


Figure 6-100: Amygdaloidal top of a basaltic lava, Trotternish, Skye. Coin *ca*. 20 mm across.



Figure 6-101: Pipe amygdales, basaltic lava, Greep, Trumpan, Waternish, Skye. Coin *ca*. 24 mm across.



Figure 6-102: Large gas cavities partially filled with hydrothermal minerals. The left-hand cavity is coated by prismatic crystals and the right-hand cavity by fibrous crystals. Both are members of the zeolite group of minerals (not determined). Coin *ca.* 24 mm across.



Figure 6-103: Intensely hornfelsed (contact metamorphosed) amygdaloidal basaltic lava adjacent to the southern margin of the Cuillin Intrusive Centre, Skye. Coin *ca.* 24 mm across.

Within a lava field there may be a zonal distribution of the amygdale minerals related to depth of burial or the effect of later central complexes, as demonstrated in the classic study of the Mull Lava Field by Walker (1971) (Figure 6-104; Figure 6-105).

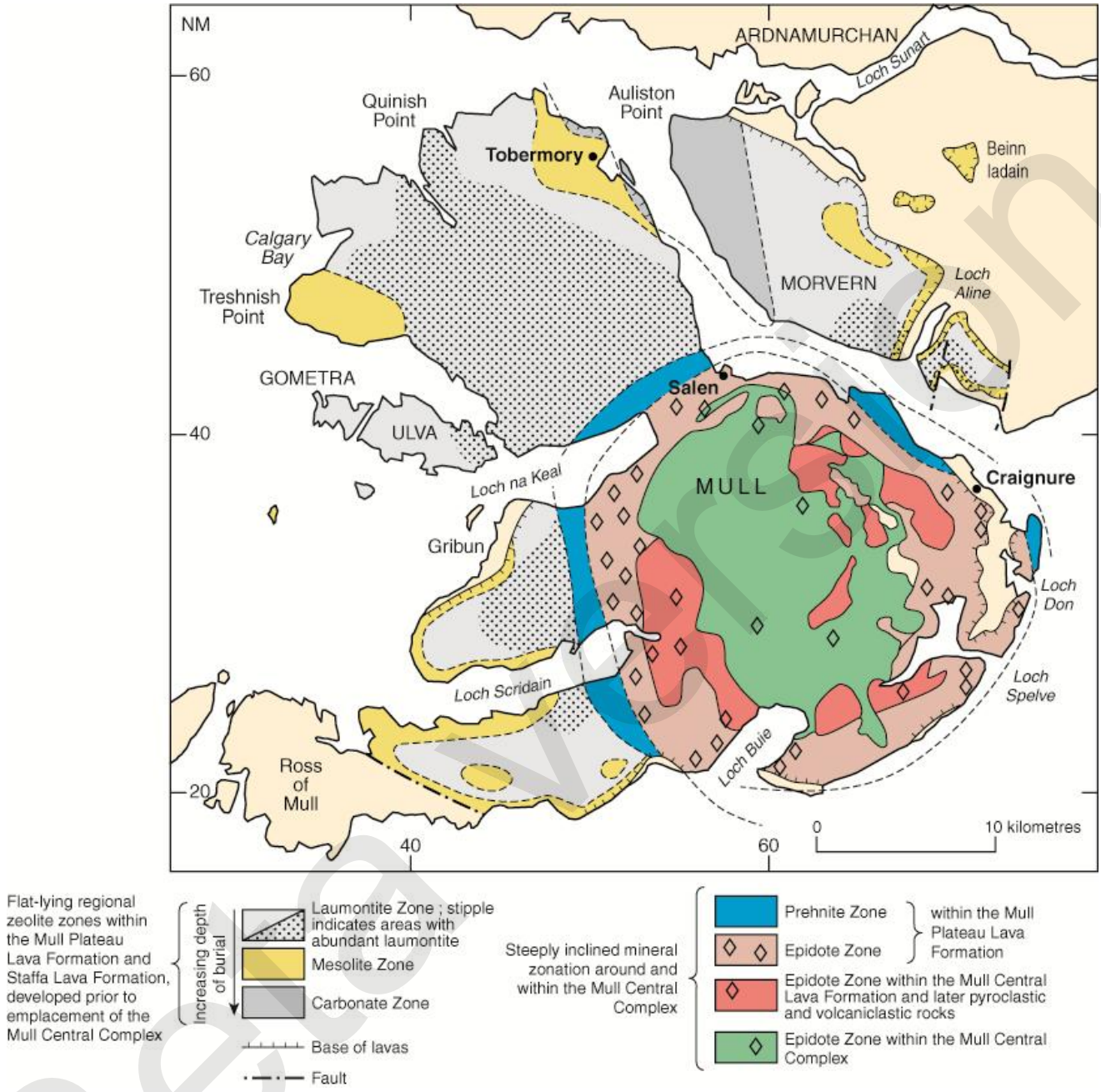


Figure 6-104: Distribution of hydrothermal mineral zones within the lavas of the Mull Lava Field on Mull and Morvern (after Walker 1971).

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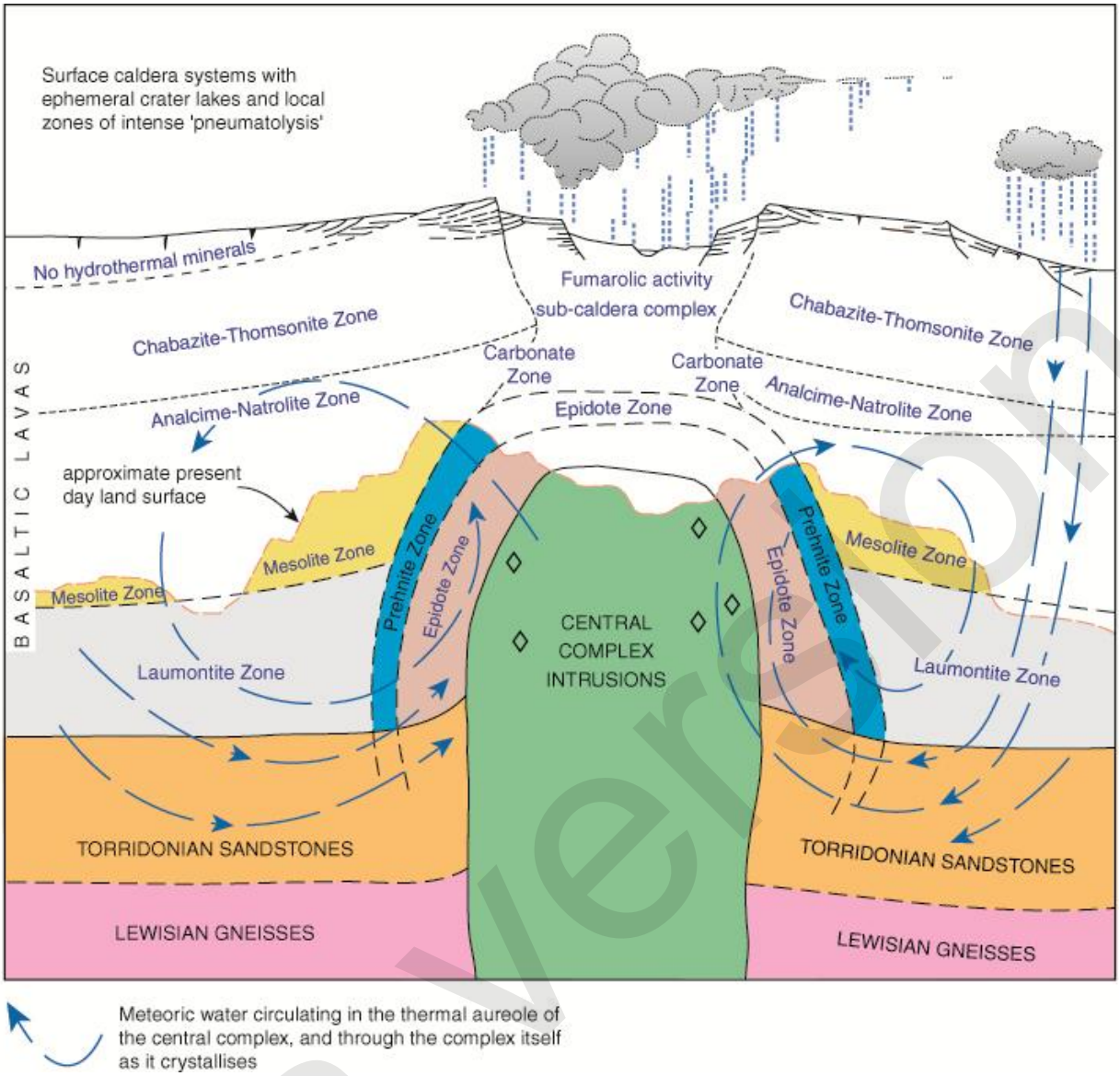


Figure 6-105: Schematic section illustrating the concept of the circulation of hydrothermal fluids around the Mull Central Complex (after Walker 1971).

Hawaiite and mugearite lavas are generally less vesicular, indicative of a lower dissolved volatile content upon eruption, although some trachytes are distinctly vesicular/amygdaloidal, for example, the trachye lava below the Preshal Beg Conglomerate Formation in Glen Sleadale, Minginish.. The tholeiitic andesites of NW Rum are noted for their amygdales of bloodstone (green-stained chalcedonic silica flecked with red, oxidised pyrite) and banded agate, both of which occur in the beach deposits at Guirdil.

6.4.6 Palaeosols

Palaeosols or laterites are layers of weathered rock which can develop on the top surfaces of lavas or, more readily, pyroclastic rocks such as tuffs (lithified ash deposits). Their thickness will depend upon the ease of weathering, faster in fragmental material, the time interval that material is exposed to the atmosphere before burial by younger material, and the climate. Throughout the Paleocene, within the HIP, the climate was warm temperate, with moderate to high rainfall on free-draining ground. Where palaeosols are absent, this may be attributed to the relatively rapid and near-continuous aggradation of the volcanic sequence, although factors such as erosion of weathered material may also be important in

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terms of what is preserved. Complexities of a lava field can be such that a significant palaeosol can develop at one location, whilst elsewhere it is absent due to simultaneous lava accumulation.

Typically, the palaeosols are (present day) weathered and obscured inland, but are well exposed in the sea cliffs. They range in colour from dark chocolate-brown through dull reddish brown to bright ocherous red, and from grey to mauve (Figure 6-106; Figure 6-107; Figure 6-108; Figure 6-109; Figure 6-110; Figure 6-111; Figure 6-112; Figure 6-113; Figure 6-114). They are generally not preserved in the vicinity of the central complexes, where pervasive hydrothermal alteration has commonly reduced lavas and palaeosols alike to dull, grey rocks.



Figure 6-106: Palaeosol top to a basaltic lava, roadcut south of Ensay, NW Mull. Ian Williamson for scale.



Figure 6-107: Palaeosol top to a basaltic lava, overlain by prismatic-jointed lava, north coast of Loch Scridain, SW Mull.



Figure 6-108: Palaeosol development on a basaltic lava, Storr cliff section, Trotternish, Skye.



Figure 6-109: Palaeosol development on basaltic lavas, NW Oronsay, Loch Bracadale, west-central Skye.

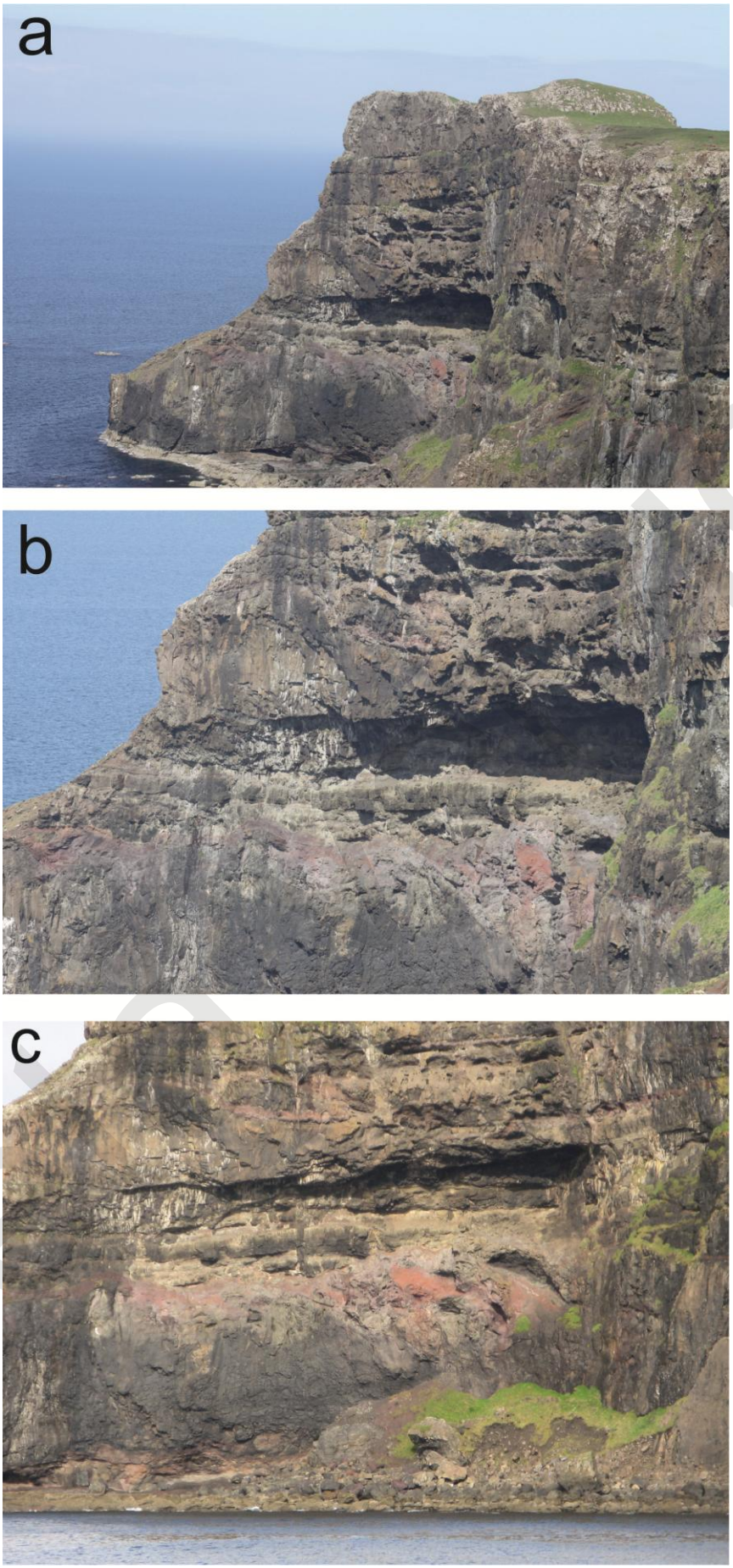


Figure 6-110: Palaeosol development on a mugearite lava, Rubha Cruinn, north side of Talisker Bay, west-central Skye.



Figure 6-111: Weathered, brecciated top of a compound basaltic lava, An Stac, south side of Talisker Bay, Minginish, west-central Skye. Pole *ca*. 1 m long.



Figure 6-112: Weathered top to a basaltic lava and complete alteration/oxidation of an overlying tuff (bright orange), Port Mòr, SE Muck. The weathering/alteration process was halted when the overlying vesicular lava was added to the sequence and thus preserved the profile. Pole *ca*. 1 m long.



Figure 6-113: Detail of weathered top to a basaltic lava and complete alteration/oxidation of an overlying tuff (bright orange), Port Mòr, SE Muck. The weathering/alteration process was halted when the overlying vesicular lava was added to the sequence and thus preserved the profile. Pole *ca.* 1 m long.



Figure 6-114: Palaeosol development at top of basaltic lava (not shown), south side of Beinn Iodain, Morvern. Hammer *ca.* 35 cm long.

In a few instances, the thicker beds preserve crude rhizolith-like structures where mineral matter has replaced plant roots. Such features are taken to indicate that the palaeosols formed *in situ*. The thickest and best developed palaeosols occur in intimate association with thin mudrocks. The latter are generally

preserved as lensoid bodies on the undulating, eroded tops to lavas and palaeosols, and point to minor reworking of soil and volcanic ash by running water, most likely rainwater run-off rather that organised fluvial systems. Commonly, these thicker palaeosols (with or without associated mudstone) are immediately overlain by thick, differentiated lavas of hawaiite or mugearite, suggesting prolonged periods between eruptions. Particularly good examples occur at Carbost, Talisker Bay, Beinn nan Dubh Loch, Fiskavaig and Biod Mór, all in Minginish, west-central Skye (Figure 6-115).

Palaeosol-like layers with indistinct bedding and rudimentary pisoidal structure, commonly containing pristine minerals such as sanidine, biotite and pyroxene, are interpreted as the product of contemporaneous weathering of crystal and vitric tuffs and not a consequence of deep-weathering of *in situ* lava. Examples include those at Lochan nan Dunan in northern Trotternish, Skye, and at Port Mòr, SE Muck (Figure 6-116; Figure 6-117).



Figure 6-115: Laminated, oxidised Eynort Mudstone Formation siltstone and mudstone, Carbost Burn, Carbost, Minginish, west-central Skye; overlying is a thick prismatic-jointed mugearite lava. Hammer *ca.* 50 cm long.

Be



Figure 6-116: Deep-weathered tuff, Lochan nan Dunan, north Trotternish, Skye. Lens cap *ca*. 8 cm across.



Figure 6-117: Deep-weathered tuff, Port Mòr, SE Muck. Pole *ca*. 1 m long.

6.4.7 Porphyritic texture

Plagioclase is by far the main and obvious phenocryst mineral in porphyritic-textured lavas within the HIP (Figure 6-118; Figure 6-119). Plagioclase-phyric olivine basalts are typically more massive and thicker than non-porphyritic lavas, such as tholeiitic basalt and tholeiitic olivine basalt lavas, although lavas of any composition may be unusually thick where ponded in palaeo-valleys.



Figure 6-118: Plagioclase macro-porphyritic basaltic lava, Dùn Ard an t-Sabhail, Minginish, west-central Skye. Coin *ca.* 24 mm across.



Figure 6-119: Plagioclase porphyritic basaltic lava, north shore of Loch Eishort, Strath, Skye. Coin *ca.* 24 mm across.

6.4.8 Flow structures

'Flow' structures are best, but not exclusively, developed within the more evolved lavas, and this 'flow banding' is generally parallel to the dip of the lava (Figure 6-120; Figure 6-121). The commonest type is due to the alignment of groundmass and microphenocryst feldspars, which impart an obvious fissility and banded appearance to the rock and is a useful aid to field identification; flow-alignment of plagioclase macrophenocrysts is not generally noted. Where the base of the flow is irregular, folding of the foliation is common. Large-scale examples include the mugearite lava at McFarlane's Rock, west-central Skye (Figure 6-122; Figure 6-123) and the basaltic lava near to the summit of Dùn Caan, Raasay (Figure 6-124; Figure 6-125), whereas smaller-scale folds are present in the tholeiitic andesite on Fionchra, Rum.

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Figure 6-120: Hawaiite lava with horizontal fabric, south side of Macleod's Table North (Healabhal Mhòr), Duirinish, west Skye. Pole *ca*. 1 m long.



Figure 6-121: Planar fabric, locally folded (right of hammer), in an hawaiite lava, south side of Arnaval, Gleann Oraid, Minginish, west-central Skye. Hammer *ca*. 30 cm long.



Figure 6-122: Folded fabric in a mugearite lava, McFarlane's Rock, north of Talisker Bay, Minginish, west-central Skye. Pole *ca.* 1 m long.



Figure 6-123: Detail of folded fabric in a mugearite lava, McFarlane's Rock, north of Talisker Bay, Minginish, west-central Skye. Ruler 30 cm long.

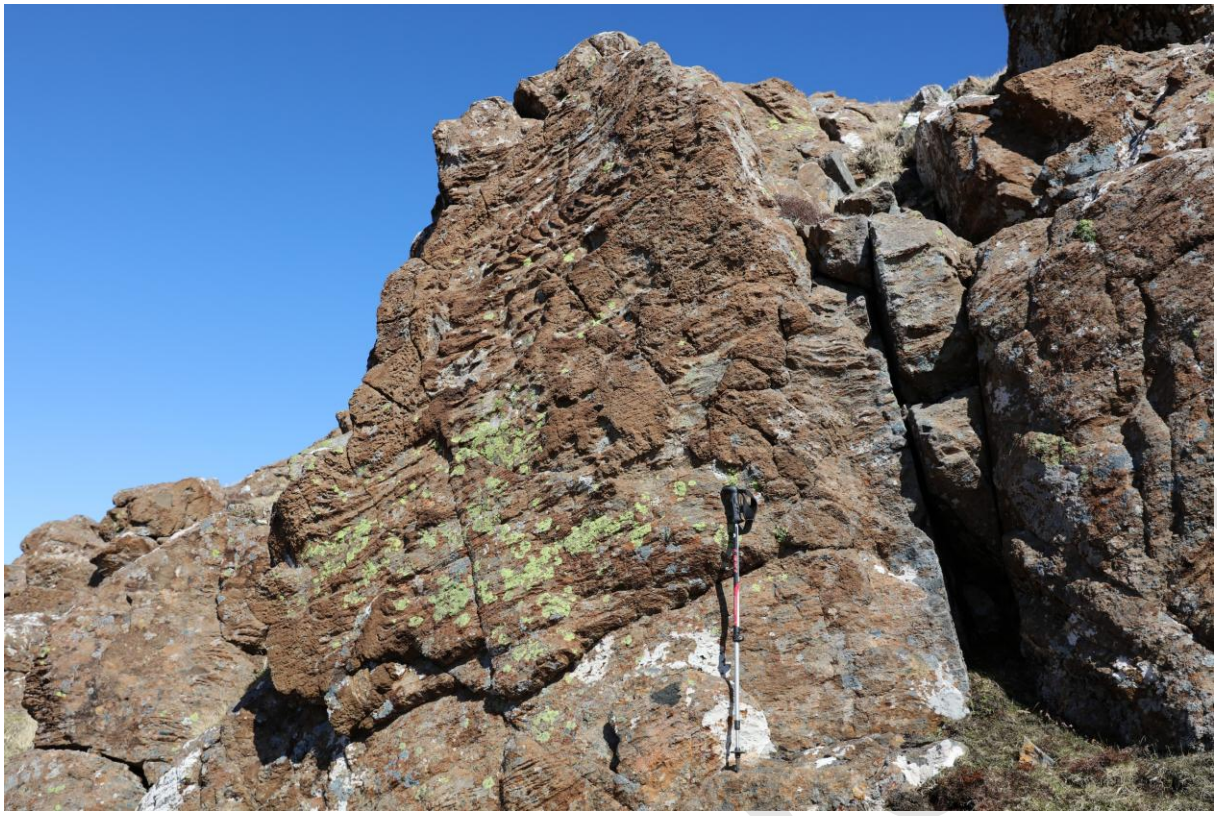


Figure 6-124: Folded fabric in a basaltic lava, west side of Dùn Caan, Raasay. Pole *ca*. 1 m long.



Figure 6-125: Detail of folded fabric in a basaltic lava, west side of Dùn Caan, Raasay. Ruler 30 cm long.

Examples of systematic and abrupt changes in the inclination of flow-banding and cooling joints occur at several localities. Usually, an otherwise flat to low-angle pattern is replaced by a near-vertical one. This could indicate either a flow dipping in an intrusive manner under its own surface or reflect the possibility of the lava having flowed over uneven topography. There are many examples, including those at Loch Dubh, Cnoc Scarall and Coir' an Rathaid, in west-central Skye.

Flow direction, albeit local, may be established where the base of a lava has over-ridden unconsolidated material such as sediment. There are good examples in lavas overlying the Minginish Conglomerate Formation in the Allt Mòr between Loch Brittle and Loch Eynort, west-central Skye. There, the lavas have both 'nosed' into soft sediment, incorporating strings of sandy material, and have inclined 'flame-like' masses of sediment along their bases (Figure 6-126). Another good example of sediment 'flames' within the base of a basaltic lava is at Traigh Cadh' an Easa, south coast of Brolass, SW Mull (Figure 6-127). Flow direction may also be indicated by inclined or deflected pipe-amygdales and by discoid amygdales.



Figure 6-126: Lava lobe intruded into siltstone of the Minginish Conglomerate Formation, Allt Mòr, Minginish, west-central Skye.

Be



Figure 6-127: Sediment 'flame' within the base of a basaltic lava, Traigh Cadh' an Easa, south coast of Brolass, SW Mull. Ian Williamson for scale.

6.4.9 Joints

The extent to which columnar joints have developed in lavas appears to depend, amongst other things, on the composition of the magma. The best examples of columnar joints typically occur in tholeiitic basalt or tholeiitic olivine basalt lavas, and the most celebrated example of a columnar jointed lava in the Hebridean Igneous Province is the tholeiitic basalt lava at Fingal's Cave on Staffa (Figure 6-128; Figure 6-129; Figure 6-130; Figure 6-131).

Beta version



Figure 6-128: Inclined Fingal's Cave Lava, south coast of Staffa, overlying bedded hyaloclastite, with columnar-jointed colonnade and overlying 'wavy' jointed entablature. Top of lava removed by present-day erosion. Height of cliff 42 m.



Figure 6-129: Inclined Fingal's Cave Lava, south coast of Staffa, overlying bedded hyaloclastite, with columnar-jointed colonnade and overlying 'wavy' jointed entablature. Top of lava removed by present-day erosion. Height of cliff 42 m.



Figure 6-130: Inclined Fingal's Cave Lava, south coast of Staffa, overlying bedded hyaloclastite, with columnar-jointed colonnade and overlying 'wavy' jointed entablature. Top of lava removed by present-day erosion. Height of cliff 42 m, with person for scale.

Beta version



Figure 6-131: The Great Face of the Fingal's Cave Lava, south coast of Staffa, overlying bedded hyaloclastite, with columnar-jointed colonnade and overlying 'wavy' jointed entablature. Top of lava removed by present-day erosion. Height of cliff is 42 m, indicating a lava thickness in excess of *ca.* 40 m.

To repeat points made elsewhere in this volume, the joint patterns in columnar-jointed lavas are a product of volume reduction of magma during crystallisation and stress release at sub-magmatic temperatures. A lava is referred to as being columnar-jointed if the columns are perfectly hexagonal (or near perfectly, for example, pentagonal and heptagonal), having developed orthogonal to the cooling surface: vertical on a horizontal land surface, horizontal against, for example, a vertical valley wall. Less perfect joints are referred to as being prismatic (Figure 6-132; Figure 6-133; Figure 6-134; Figure 6-136; Figure 6-137; Figure 6-138). Curved columnar joints are also relatively common, indicative of more complex cooling histories (Figure 6-135)

In many columnar-jointed lavas, the upper portion comprises more complex 'wavy' joints (Figure 6-136). In such lavas, the lower more perfectly jointed portion is referred to as the colonnade and the upper complex portion as the entablature. Commonly there is a remarkably sharp boundary between the two joint facies (Figure 6-137; Figure 6-138). Columnar-jointed lavas commonly develop when a simple flow (partially) infills valleys (topogaphic lows) with active drainage systems. The joint distribution pattern is interpreted as the product of the lower portion of the lava, once it has stopped flowing, loosing heat through its floor, commonly on a wet substrate, producing the colonnade, whilst the upper portion, the entablature, results when water ingresses the top of the lava, typically when the drainage system has been re-established.

Beta Version



Figure 6-132: Colonnade portion of the Fingal's Cave Lava, south coast of Staffa, overlying bedded hyaloclastite.



Figure 6-133: Colonnade causeway of Am Buachaille, west coast of Staffa.



Figure 6-134: Pentagonal, hexagonal and heptagonal columns of the colonnade portion of the Fingal's Cave Lava, south coast of Staffa. Pole *ca*. 1 m long.



Figure 6-135: Curved columnar joints, Clamshell Cave, Staffa.

Proof version



Figure 6-136: Entablature portion of the Fingal's Cave Lava, south coast of Staffa.



Figure 6-137: Boundary between colonnade portion and entablature portion of the Fingal's Cave Lava, south coast of Staffa.



Figure 6-138: Boundary between colonnade portion and entablature portion of the Fingal's Cave Lava, south coast of Staffa.

Details of the columnar structure and other related features are well exhibited on Preshal More and Preshal Beg, Minginish, in west-central Skye, where the tholeiitic olivine basalt lava of the Talisker Formation, over 120 m thick, forms two outliers on the lava plateau. Here, a single intra-canyon lava erupted into a river channel which already contained debris flow and fluvial sediments. Locally, hyaloclastite with pillows formed where magma interacted with water, prior to the main extrusive event (Figure 6-139). The lava then partially filled the steep-sided valley ('canyon'), after which the drainage system was re-established. The colonnade formed by cooling through the base (valley floor) and sides (valley sides), and the entablature joints formed due to water ingress from the top from the re-established drainage system (Figure 6-140; Figure 6-141). Inclined columns of the colonnade at several localities indicate the proximity of the sidewalls of the palaeo-valley in which the magma ponded, but which have been subsequently removed by erosion (Figure 6-142). The top of the Preshal Beg outcrop has an 'invasive' facies of the lava, where there are auto-intrusive sheets above the entablature (Figure 6-143).

Beta version



Figure 6-139: Pillows in hyaloclastite at the base of the Talisker Formation lava, south side of the Preshal Beg outcrop, Minginish, Skye. Ruler 30 cm long.



Figure 6-140: Colonnade and entablature on the south side of the Preshal More outcrop of the Talisker Formation lava, Minginish, Skye.

Draft version



Figure 6-141: Colonnade and entablature on the south side of the Preshal More outcrop of the Talisker Formation lava, Minginish, Skye.



Figure 6-142: Inclined columns of the colonnade in contact with hyaloclastite (pale weathered), produced by magma-water interaction during the initial stages of the eruption of the Talisker Formation lava, north face of Preshal More, Minginish, Skye.



Figure 6-143: In ascending order: colonnade, entablature and invasive sheet facies of the Talisker Formation lava on the south side of the Preshal Beg outcrop, Minginish, Skye.

Spectacularly jointed lavas of the Staffa Lava Formation of the Mull Lava Field occur elsewhere: on the south coast of Brolass, from Carraig Mhòr, west to Port nan Droigheann (Figure 6-144; Figure 6-145); on Ardmeanach, in the Macculloch's Tree coastal section (Figure 6-146; Figure 6-147; Figure 6-148; Figure 6-149); and, at Ardtun on the north coast of the Ross of Mull (Figure 6-150; Figure 6-151).



Figure 6-144: Columnar-jointed basaltic lavas, Malcolm's Point cliff, south Brolass, SW Mull.



Figure 6-145: Columnar-jointed basaltic lava, Carsaig Arches, Malcolm's Point, south Brolass, SW Mull.



Figure 6-146: Columnar-jointed Macculloch's Tree Lava, south of Rubha na h-Uamha, Ardmeanach, SW Mull. Tree mould located left of centre, at back of gravel beach.



Figure 6-147: Mould of Macculloch's Tree, south of Rubha na h-Uamha, Ardmeanach, SW Mull, with columnar joints orthogonal to the tree due to the influence of the tree during cooling of the lava. Henry for scale.

Be



Figure 6-148: Complex columnar joint patterns, Macculloch's Tree Lava, south of Rubha na h-Uamha, Ardmeanach, SW Mull. John Faithfull for scale.



Figure 6-149: Radiating columnar joints in the vicinity of a vertical cavity, interpreted as a mould of an upright fossil tree, similar to Macculloch's Tree, Ardmeanach, SW Mull. Ian Williamson and Graham McLeod for scale.



Figure 6-150: Columnar-jointed basaltic lava, Port Uamh na Gaibhre, north of Ardtun, Ross of Mull, SW Mull.



Figure 6-151: Columnar-jointed basaltic lava, Port Uamh na Gaibhre, north of Ardtun, Ross of Mull, SW Mull, overlain by strata of the Ardtun Conglomerate Member of the Staffa Lava Formation (above grass slope), capped by a prismatic-jointed basaltic lava.

Excellent examples of columnar-jointed lavas also occur on Canna, within the Canna Lava Formation, in close association with sedimentary units, for example at Compass Hill in east Canna (Figure 6-152).



Figure 6-152: Columnar-jointed basaltic lavas interbedded with clastic strata of the Canna Lava Formation, Compass Hill, east Canna.

On Rum, the hawaiite lava that unconformably overlies the Paleocene Western Granite on the north side of Orval has imperfectly developed prismatic joints (Figure 6-153).



Figure 6-153: Prismatic-jointed hawaiite lava, north side of Orval, NW Rum.

The rhyodacitic lava-like ignimbrite, which forms An Sgùrr on the island of Eigg (the 'Sgùrr of Eigg') contains superb columns, typically smaller-spaced than those of basaltic lavas and highly irregular in places. The cooling history of this valley-fill ignimbrite is complex, resulting in intricate joint patterns (Figure 6-154; Figure 6-155; Figure 6-156; Figure 6-157; Figure 6-158).



Figure 6-154: Valley-fill, lava-like ignimbrite forming the inverted topographic feature of An Sgùrr, Eigg.



Figure 6-155: Complex cooling joint sets within the valley-fill, lava-like ignimbrite forming the inverted topographic feature of An Sgùrr, Eigg.

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Figure 6-156: Complex cooling joint sets within the valley-fill, lava-like ignimbrite forming the inverted topographic feature of An Sgùrr, Eigg.



Figure 6-157: Complex cooling joint sets within the valley-fill, lava-like ignimbrite forming the inverted topographic feature of An Sgùrr, Eigg.

Preview



Figure 6-158: Complex cooling joint sets within the valley-fill, lava-like ignimbrite forming the inverted topographic feature of An Sgùrr, Eigg.

A similar ignimbrite crops out on the SE side of Ben Hiant, Ardnamurchan. The cooling joint pattern is simpler, developed orthogonal to the dipping base of the unit(s) (Figure 6-159).



Figure 6-159: Prismatic-jointed, lava-like ignimbrite, SE Ben Hiant, Ardnamurchan.

Beta version

Columnar-jointed basalt lavas are common on Canna, mostly accessible in the south side of the island, north of Tarbert Bay (Figure 6-160).



Figure 6-160: Columnar-jointed basaltic lavas, south Canna, north of Tarbert Bay.

Beta version

6.4.10 Peperite

The interaction of magma in the volcanic environment with unlithified sediment with pore water results in a thoroughly heterogeneous mixed rock referred to as a peperite. Its development can be very local, although in some instances large volumes can be produced. Perhaps the best example in the HIP occurs at Carraig Mhòr, east of Carsaig, Brolass, SW Mull, with the striking colour contrast between the dark silty mud(stone) and the pale, carbonate-altered basaltic lava (Figure 6-161; Figure 6-162; Figure 6-163; Figure 6-164). The shapes of the volcanic fragments range between fluidal, with intricately curved margins, and relatively angular shapes.



Figure 6-161: Peperite, comprising pale, carbonate-altered basalt fragments with curved, fluidal margins within a matrix of dark siltstone, Carraig Mhòr, east of Carsaig, Brolass, SW Mull. Compass *ca*. 10 cm long.

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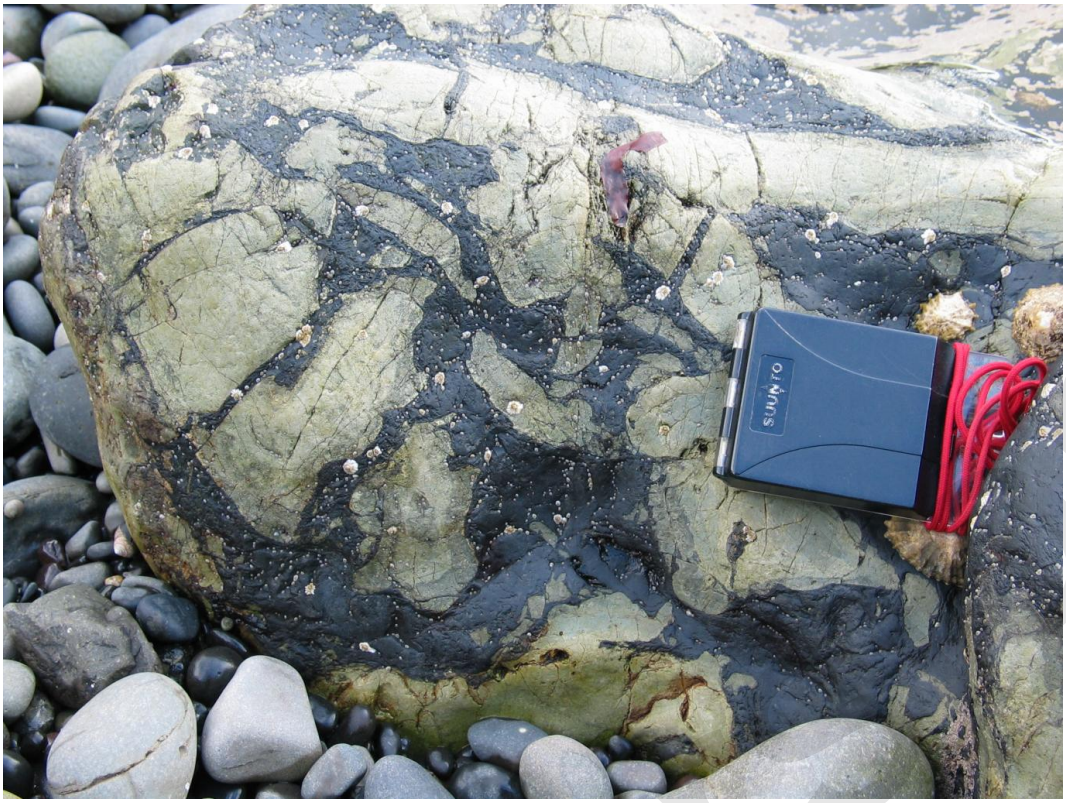


Figure 6-162: Peperite, comprising pale, carbonate-altered basalt fragments with curved, fluidal margins within a matrix of dark siltstone, Carraig Mhòr, east of Carsaig, Brolass, SW Mull. Compass *ca*. 10 cm long.



Figure 6-163: Peperite with a wide range of pale igneous fragment sizes, mostly with fluidal margins, especially the larger fragments, Carraig Mhòr, east of Carsaig, Brolass, SW Mull. Hammer *ca*. 30 cm long.

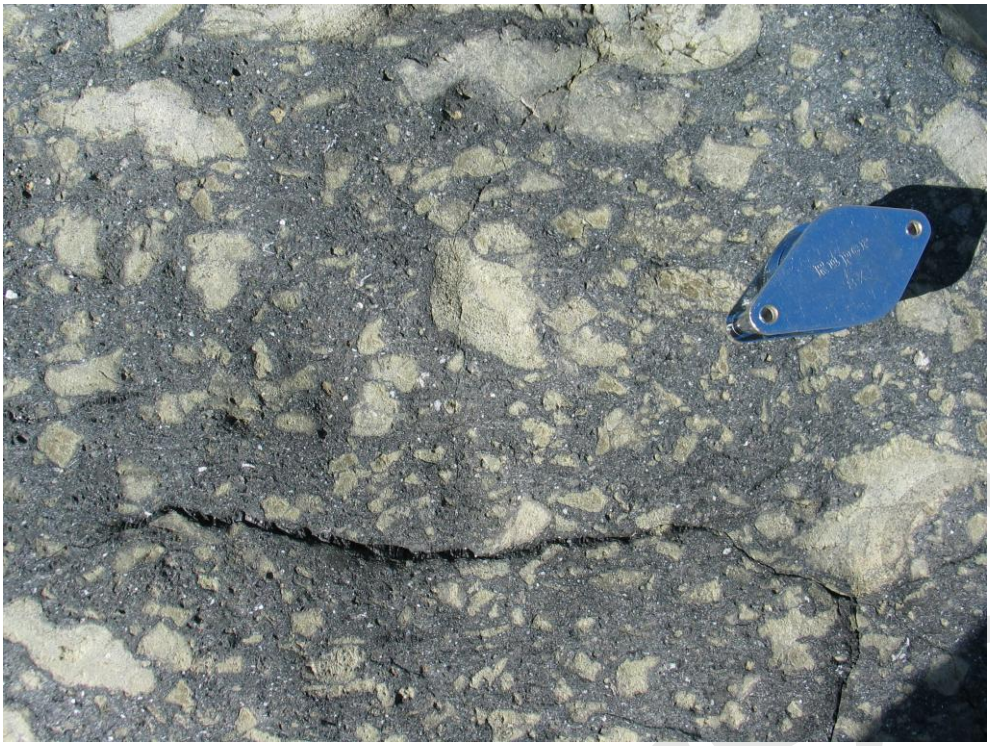


Figure 6-164: Peperite with a wide range of pale igneous fragment sizes, ranging between fluidal and angular shapes, Carraig Mhòr, east of Carsaig, Brolass, SW Mull. Lens *ca.* 7 cm long.

Peperite can also occur in very restricted pockets close to the margins of lavas, for example in SE Sanday, at the base of the rock pillar, Dùn Beag (Figure 6-165; Figure 6-166), and where thin sheets of basalt are injected into sedimentary units (Figure 6-167).



Figure 6-165: Insipient peperite development at lava-sediment interface, base of Dùn Beag rock pillar, SE Sanday, with flame-like projections of pale lava into dark laminated sediments, and vice versa. Lens cap *ca.* 8 cm across.

Browser version



Figure 6-166: Pocket of peperite at boundary between pale (carbonate altered) lava (top) and dark, laminated siltstone (bottom), base of Dùn Beag rock pillar, SE Sanday. Lens cap *ca*. 8 cm across.



Figure 6-167: Interaction between (Paleocene) basalt injected into Middle Jurassic (Skudiburgh Formation) sandstone, with obvious vesiculation. Coin *ca*. 24 mm across.

6.4.11 Weathering

Weathering style is a useful field characteristic of lava type or composition. The minerals in basaltic lavas, commonly (relatively) rich in olivine, tend to alter more readily than those in the more evolved types, such as hawaiite and mugearite. Coupled to the more obviously amygdaloidal and usually coarser grained nature of the olivine basalts, this results in the degradation of rock faces and a tendency for basaltic lavas to form hollows or lower ground ('slacks') or terraced slopes between more resistant-to-weathering evolved lavas. Within individual lavas, the amygdaloidal tops and bases weather more readily than the massive centres, contributing to the development of the characteristic 'trap-featuring' (Figure 6-168; Figure 6-169).



Figure 6-168: Prismatic-jointed mugearite lava capping poorly exposed (vegetated) basaltic lavas, Leathad Beithe, south side of Talisker Bay, Minginish, west-central Skye.



Figure 6-169: Poorly exposed lavas on SE side of Fionchra, NW Rum

Beta version

6.5 The Skye Lava Field

6.5.1 Skye

6.5.1.1 Introduction

A usable and practical approach to subdividing the lava-dominated sequences of Trotternish, Waternish and Duirinish of north Skye was first applied by Anderson & Dunham (1966) when they proposed five groups, separated by sedimentary units. The simple principle is that the sedimentary units represent (substantial?) hiatuses in the volcanism, during which, normal background sedimentation, mainly fluvial and lacustrine, re-established. If this principle/interpretation is correct, then the various subdivisions also have a chrono-stratigraphic significance; however, there is the distinct possibility that sedimentation in one part of the lava field could have been contemporaneous with weathering or erosion or volcanism elsewhere in the lava field. A similar, but more detailed approach was applied to the sequences in Minginish, west-cental Skye, by Williamson & Bell (1994). Other disparate outcrops cannot be placed in an absolute stratigraphic scheme.

On the basis of field observations reported in Anderson & Dunham (1966), England (1994) concluded that the overall structure of the lava field is a syncline that, in part, trends parallel to the NW-SE -trending Skye Main Dyke Swarm (Figure 6-170) (Chapter 7). This structure is attributed to the loading effect of the lava pile as it aggraded. Deviations away from this trend, towards N-S and NE-SW, are attributed to later tectonic processes in the Oligocene, possibly related to the N-S -trending Canna Fault.

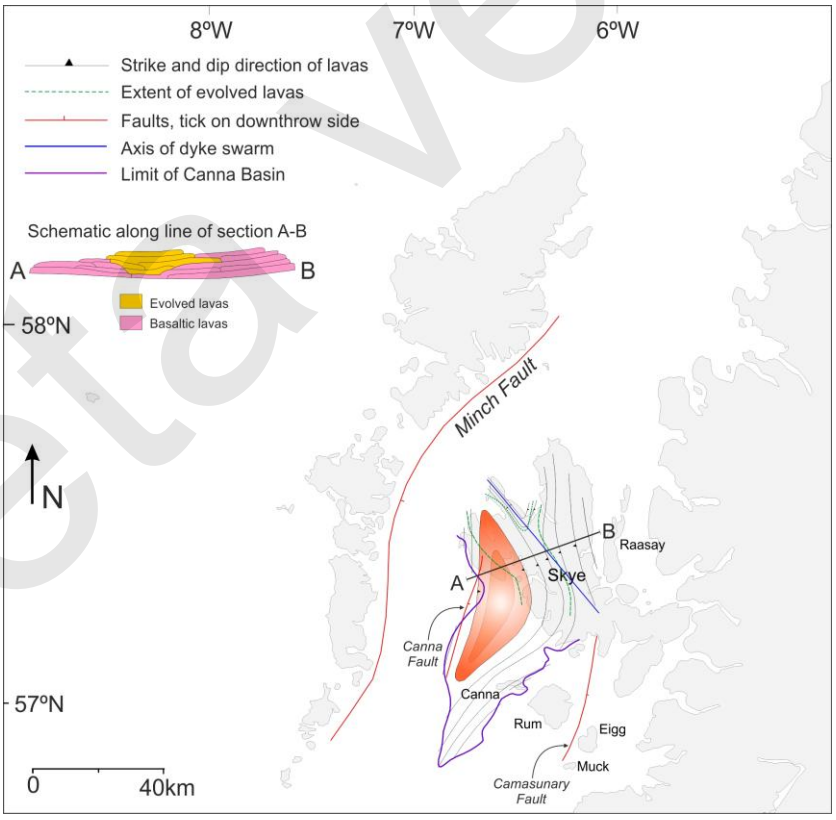


Figure 6-170: Structural map of the Skye Lava Field illustrating a simplistic schematic cross-section with evolved lavas more abundant within the central part of the syncline (after England 1994).

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6.5.1.2 Trotternish, Waternish and Duirinish (North Skye)

The area documented by Anderson & Dunham (1966) was originally surveyed by the British Geological Survey between 1934 and 1939 by D. Haldane, J. Knox, T. R. M. Lawrie and T. Robertson, with G. V. Wilson as District Geologist; the 1966 memoir was an attempt to unify the field data collected by the geologists involved. A subsequent formal addition to the lithostratigraphic framework of Anderson & Dunham (1966) was incorporated in a desk revision of the 1:50,000 maps published in the 2000s (BGS 2006b; BGS 2006c; BGS 2007), with the recognition of a hyaloclastite-dominated basal unit north of Portree, the Portree Hyaloclastite Formation (Figure 6-171).

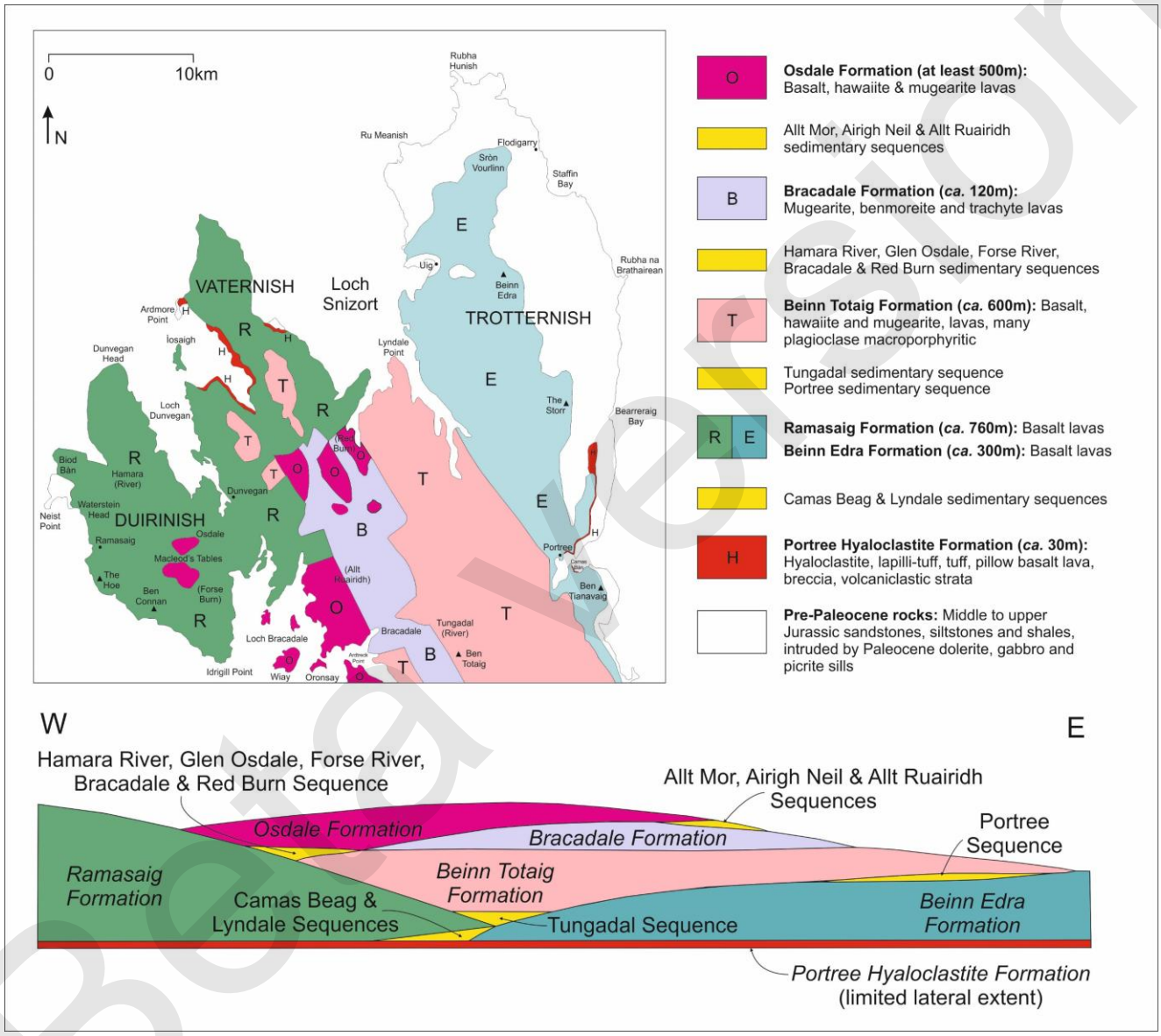


Figure 6-171: Simplified schematic geological map and cross-section illustrating the distribution of the five lava formations and interbedded sedimentary sequences in North Skye (after Anderson & Dunham 1966).

The Portree Hyaloclastite Formation is the oldest recognised subdivision of the lava field stratigraphy and is up to 30 m thick. The best exposed and most continuous outcrops are located north of Portree, forming an inland set of crags between Sìthean a' Bhealaich Chumhaing and Fiurnean, including the crags of Craig Ulatota, along the eastern margin of the Beinn Edra Formation outcrop. Here, the base of the volcanic sequence is not exposed, with the underlying Lower and Middle Jurassic strata intruded by dolerite sills

Beta Version

forming the coastal cliffs to the east (Chapter 8). The formation also crops out: further to the south at Rubha na h-Àirde Glaise; further west, in the east bank of a tributary of the Lòn Druiseach; poorly on the north side of Loch Portree, east of Toravaig; and, on the south side of Loch Portree at Camas Bàn (Figure 6-172). Other very small exposures occur where the base of the volcanic sequence is exposed in north Skye but are typically of poor quality and of a discontinuous nature, for example at Creagan na Sgalain on the north side of Tianavaig Bay, and south along the east-facing coast as far as Peinachorrain. Significant post-glacial landslips in north Skye have affected the basal part of the volcanic sequence (Chapter 13) and have significantly obscured the Portree Hyaloclasite Formation, although found as displaced fragments, for example at Staffin and Flodigarry.



Figure 6-172: The Portree Hyaloclastite Formation on the west side of Camas Bàn, east of Vriskaig Point on the south side of Loch Portree.

The sequence is relatively heterogeneous, with significant along-strike variation. Considering the main exposures, detailed above, the dominant lithology is hyaloclastite, essential a poorly stratified breccia composed of matrix-supported fragments of fine-grained to glassy basalt, commonly angular, up to 20 cm across, but typically <5 cm across, in a matrix of similar, much finer-grained or glassy material (Figure 6-173). The overall colour of the hyaloclastite is mid to dark brown, contrasting with the very pale/white zeolites and carbonate that has commonly been precipitated in voids throughout the rock. The larger fragments are crystalline, many with obvious chilled margins, whereas the smaller and interstitial fragments are fine-grained or, more typically, glassy. The fluids responsible for the precipitation of the interstitial hydrothermal minerals have also caused alteration of the original glass (sideromelane), to palagonite (a low temperature alteration product formed when hydrothermal fluids react with (typically) basaltic glass producing, amongst other things, microscopic crystals of various types of clay).



Figure 6-173: Detail of the Portree Hyaloclastite Formation on the west side of Camas Bàn, east of Vriskaig Point on the south side of Loch Portree Bay. Hammer *ca.* 30 cm long.

Also present within the hyaloclastite are well-developed, typically isolated, pillows of basalt, with chilled rinds and radially disposed joints, set in a matrix of hyaloclastite, and relatively rare and discontinuous beds of fine-grained, plant-bearing, volcaniclastic sedimentary rocks, typically fine-grained sandstones, siltstones and mudstones. These clastic units have previously been described as tuffs, consisting of ash, lapilli and bombs (Anderson & Dunham 1966), but show evidence of sedimentary transport and are also associated with low-grade, lignitic coals. Plant fragments within the volcaniclastic beds include Ginkgo (maidenhair) and Equisetum (horsetail). Spatially associated flat-lying sheets of jointed, commonly amygdaloidal basalt and dolerite may be thin lavas or shallow-level intrusive bodies.

In north Skye, Anderson & Dunham (1966) have assigned the overlying lava-dominated sequence to five formations, separated by laterally-impersistent sedimentary units, as detailed in Figure 6-171. Although the principle applied is robust, the lack of continuous exposure and the variable nature of these sedimentary units may imply that the interpretation presented in Figure 6-171 is not, in all instances, correct. However, at a simplistic level, it has value, indicating hiatuses, even if only geographically localised, in the aggradation of the lava field. Details of the dominant lava types in each formation (basalt, hawaiite, mugearite, benmoreite, trachyte) are summarised in Figure 6-171.

Clearly, the Beinn Edra and Ramasaig formations are, for the eastern and western parts of north Skye, respectively, the oldest sequences. Similarly, the upper part of the sequence appears to comprise, from oldest to youngest, the Beinn Totaig, the Bracadale and the Osdale formations. In map view, the distribution of these formations is shown in Figure 6-171. The intervening sedimentary intervals comprise a wide variety of clastic lithologies, ranging between cobble conglomerate and mudstone, together with low-grade coals, all deposited in fluvial and/or lacustrine environments on a relatively subdued lava field

Beta version

topography. Plant remains, typically leaves, within the fine-grained lithologies include Quercus, Corylus and Platanus, oak, hazel and plane, respectively.

The ‘type sections’ for the five recognised formations are located as follows: the Beinn Edra Formation on Beinn Edra and along the east-facing escarpment of Trotternish (Figure 6-174; Figure 6-175; Figure 6-176; Figure 6-177; Figure 6-178); the Ramasaig Formation at Ramasaig on the west-facing sea-cliffs of Duirinish and, in general, on Duirinish and Waternish (Figure 6-179; Figure 6-180; Figure 6-181; Figure 6-182; Figure 6-183); the Beinn Totaig Formation, at the head of Glen Vidigill, NE of Loch Harport, and in a swath of land between Lyndale Point at the head of Loch Snizort Beag and Ben Lee, north of Loch Sligachan (

Figure **6-184**); the Bracadale Formation (Figure 6-185; Figure 6-186) in poorly exposed ground SW of the Beinn Totaig Formation, between Roineval (NE of the head of Loch Harport) and the moorland south of Blackhill, south of the head of Loch Greshhornish; and, the Osdale Formation, in the coastal area between Glen Ose and Glen Osdale, in and north of Loch Bracadale (Figure 6-187; Figure 6-188; Figure 6-189; Figure 6-190; Figure 6-191; Figure 6-192).



Figure 6-174: Beinn Edra Formation lava sequence forming the cliffs east of Craig Ulatota, Trotternish, Skye.

Bid version



Figure 6-175: Beinn Edra Formation lava sequence forming the cliffs east of Craig Ulatota, Trotternish, Skye.



Figure 6-176: Basaltic lavas of the Beinn Edra Formation, forming the east-facing inland cliffs of The Storr on Trotternish. The coastal cliffs comprise pale Middle Jurassic Bearreraig Sandstone Formation strata intruded by a Paleocene prismatic-jointed dolerite sill. View towards the SW.

Preview



Figure 6-177: Basaltic lavas of the Beinn Edra Formation, forming the east-facing inland cliffs of The Storr on Trotternish, intruded by typically less robust thin basalt and dolerite dykes that give rise to clefts within the crags. View towards the SW.



Figure 6-178: Basaltic lavas of the Beinn Edra Formation, forming the east-facing inland cliffs of The Storr on Trotternish, intruded by typically less robust thin basalt and dolerite dykes that give rise to clefts within the crags. View towards the west.

Preview version



Figure 6-179: Basaltic lavas of the Ramasaig Formation, forming the west-facing coastal cliffs of Biod Bàn above Oisgill Bay on the west side of Duirinish.



Figure 6-180: Basaltic lavas of the Ramasaig Formation, forming the ridge of Biod an Athair on the west side of the Dunvegan peninsula, NW Skye.

Proof version



Figure 6-181: Basaltic lavas of the Ramasaig Formation, forming the southern part of the Ramasaig Cliff, Duirinish.



Figure 6-182: Basaltic lavas of the Ramasaig Formation forming Idrigill Point and Macleod's Maidens, south Duirinish.



Figure 6-183: Basaltic lavas of the Ramasaig Formation, forming the cliffs of SW Duirinish, with Healabhal Bheag (Macleod's Table South) in the distance.

Beta version



Figure 6-184: Terraced basaltic lavas of the Beinn Totaig Formation, forming Ben Grasco, *ca*. 4 km west of Portree.



Figure 6-185: Mugearite lavas of the Bracadale Formation, forming the crags of Creag Mhòr on the SE side of the Amar River, east of Bracadale, viewed towards the SE.

Proof version



Figure 6-186: Plagioclase porphyritic basalt lava of the Bracadale Formation, Roineval, north of Drynoch, Bracadale, west-central Skye.



Figure 6-187: Basaltic and mugearitic lavas of the Osdale Formation forming Healabhal Bheag (Macleod's Table South) on Duirinish, viewed towards the east. The coastal cliffs are dominated by basaltic lavas of the Ramasaig Formation.

Beta version



Figure 6-188: Basaltic and mugearitic lavas of the Osdale Formation forming the summit of Healabhal Mhor (Macleod's Table North) on Duirinish, viewed towards the south.



Figure 6-189: Basaltic and mugearitic lavas of the Osdale Group (?), Wiay, Loch Bracadale.

Beta version



Figure 6-190: Basaltic and mugearitic lavas of the Osdale Group (?), Wiay (foreground) and, beyond, Idrigill Point and Macleod's Maidens, Loch Bracadale.



Figure 6-191: Basaltic and mugearitic lavas of the Osdale Group (?), Harlosh, Loch Bracadale, with the Cuillin in the distance.

Beta version



Figure 6-192: Thick, laterally confined, volcaniclastic unit, NW coast of Oronsay, Loch Bracadale. Height of cliff *ca*. 70 m.

6.5.2 Minginish (west-central Skye)

More recent investigations of the lava field in Minginish provide a considerably more detailed breakdown of the lithostratigraphy (Williamson & Bell 1994; Bell & Williamson 2013) of that part of the Skye Lava Field, also using the principle of sedimentary interbeds indicating (local) hiatuses in the volcanism. Details are set out in Figure 6-193. Within the Minginish sequence, the most important stratigraphic break is at the base of the Preshal Beg Conglomerate Formation, which locally developed on a palaeo-land surface with significant topographic relief, and is overlain by an intra-canyon-style lava, the Preshal More Formation, that was erupted/emplaced during the shield-building stage of the Cuillin Volcano, now represented by the various gabbros, troctolites, peridotites and minor intrusions of the Cuillin Intrusive Centre (Bell & Williamson 2013) (Chapter 9).

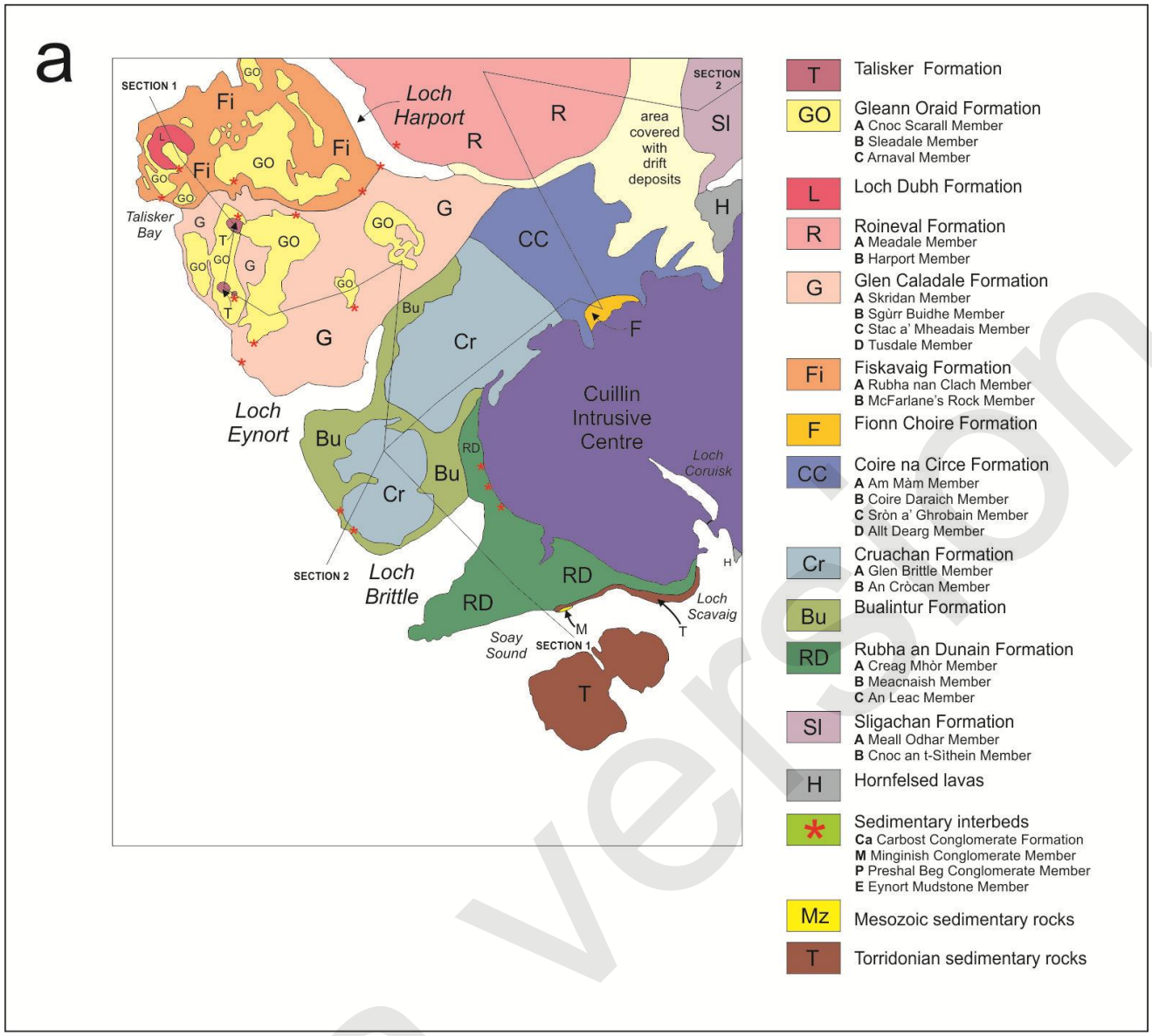
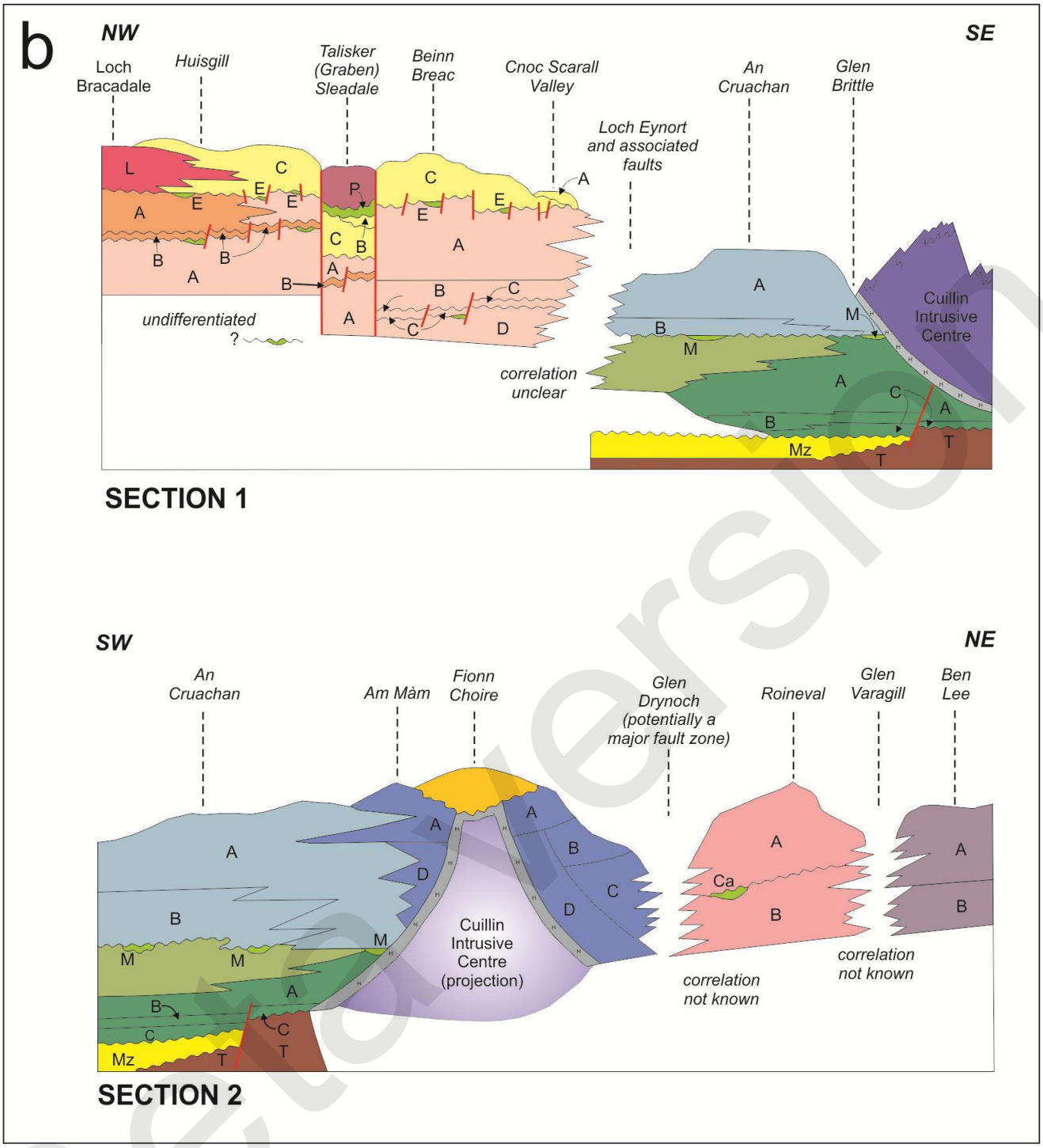


Figure 6-193: a: A simplified schematic geological map illustrating the distribution of the twelve lava-dominated formations and interbedded sedimentary sequences on Minginish and adjacent areas (after BGS 2000).

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b: Simplified schematic geological map illustrating the distribution of the twelve lava-dominated formations and interbedded sedimentary sequences on Minginish and adjacent areas (after BGS 2000).

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Figure 6-193 illustrates schematically in map and cross-section views the main subdivisions of the Minginish sequence. Twelve lava-dominated formations are recognised, some of which can be further subdivided into members (BGS 2000). All have been given local names, based upon their geographic distribution(s). The interbedded sedimentary-dominated units, also given formation status, are also detailed. The schematic cross-sections in Figure 6-193 are an attempt to illustrate the inter-relationships of these sequences, as best can be understood from the available inland and coastal exposures.

At the base of the sequence, exposed on the north side of Soay Sound at An Leac, where the Allt na Meacnaish enters the sea, the An Leac Member of the Rubha an Dùnain Formation comprises laterally impersistent units of intercalated volcaniclastic breccia and hyaloclastite, together with beds of volcaniclastic siltstone and sandstone (Figure 6-194). In some respects, this member is like the Portree Hyaloclastite Formation of north Skye (see above), indicating subaqueous deposition, most likely in a lacustrine setting, possibly with associated pyroclastic activity. This member has a thickness of *ca.* 10-20 m. It is here that the underlying Mesozoic sequence is exposed, as detailed in Chapter 3.

Above the An Leac Member are the first (oldest) lavas, attributed to the Meacnaish Member (Figure 6-194). The compositions of these lavas do not follow any simple progression with stratigraphic height; some of the oldest lavas in the sequence are mugearites.

Hiatuses in the volcanism are also evident from early in the aggradation history of the sequence, with the development of thin lacustrine shales and siltstones. The overlying Creag Mhòr Member consists of olivine ± plagioclase porphyritic and near-aphyric basaltic lavas, many with well-developed lateritic tops, with associated thin mudstones.

The two lowest lava-dominated formations, the Rubha an Dùnain and Bualintur formations (Figure 6-195), may interdigitate, and comprise a wide variety of lava types, both simple and compound, and range in composition from basalt through to mugearite. The hawaiite lavas, form strong features and can be traced laterally for significant distances, especially along the coastal sea cliffs between Loch Brittle and Loch Eynort. Porphyritic variants, mainly with olivine and/or plagioclase phenocrysts, are relatively common. Within the Bualintur Formation, for example at Sgùrr an Duine, there are thin, discontinuous beds of volcaniclastic breccia, conglomerate and sandstone, although inaccessible within the sea cliffs.

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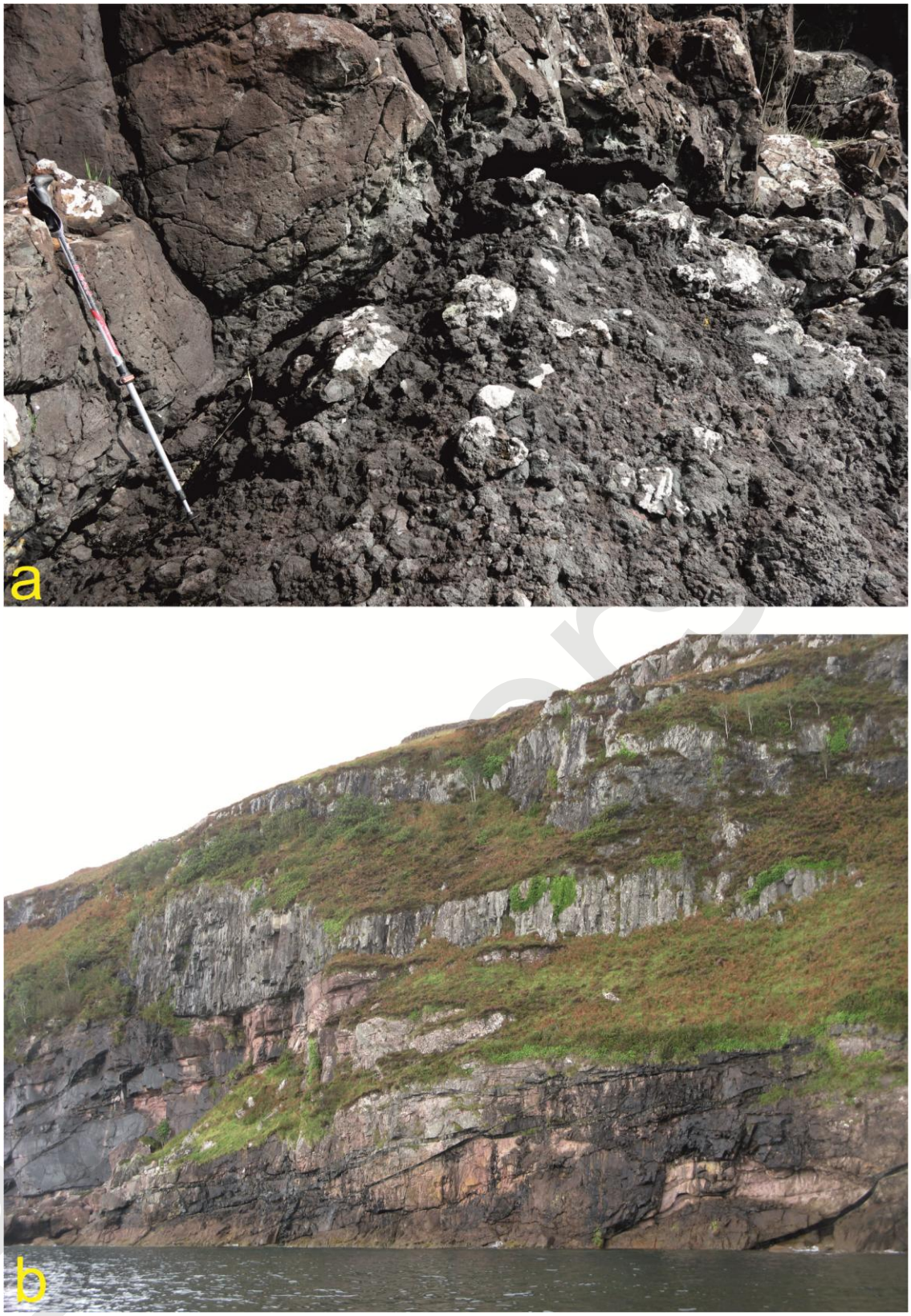


Figure 6-194: (a) Volcaniclastic breccia (bottom right) intruded by a vesicular/amygdaloidal sheet of dolerite (top left) within the An Leac Member of the Rubha an Dùnain Formation, pole *ca*. 1 m long; and, (b) prismatically-jointed evolved lavas (mugearites and hawaiites) of the Meacnaish Member (Rubha an Dùnain Formation) unconformably overlying pale orange Torridonian strata of the Bheinn Bhreac Member (Applecross Formation, Torridon Group) on the north side of Soay Sound.

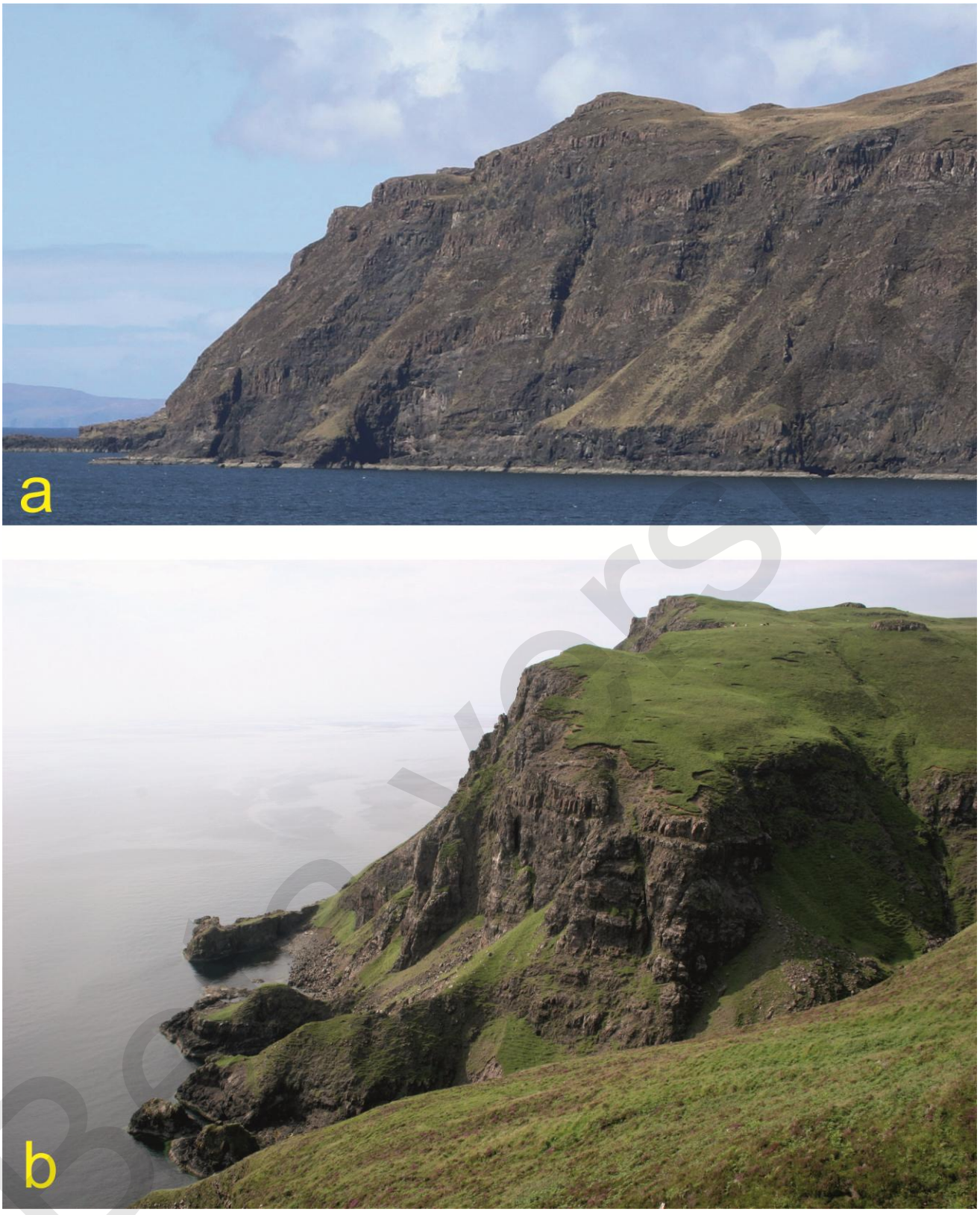


Figure 6-195: Bualintur Formation lavas, mainly of basaltic and hawaiitic composition, some prismatic, forming the coastal cliffs: (a) Geodha na h-Airigh Mòire and below An Cròcan; and, (b) Sgùrr a' Ghobhainn, west of the Allt Mòr. Both in Minginish and both views towards the NW.

The overlying Minginish Conglomerate Formation comprises a complex sequence of clastic rocks of fluvial and debris flow associations, ranging from conglomerates through to mudstones, together with thin, low-grade lignitic coals of overbank/swamp/mire association. It overlies the Rubha an Dùnain and Bualintur

formations and was deposited during a significant hiatus in the aggradation of the lava field. Three key sections/members are recognised: at Culnamean on the east side of Glen Brittle, close to the margin of the Cuillin Intrusive Centre, and in the river sections of the Allt Geodh a' Ghàmhna and the Allt Mòr, between Loch Brittle and Loch Eynort. Key features of the Allt Geodh a' Ghàmhna section/Member are illustrated in Figure 6-196, Figure 6-197, Figure 6-198 and Figure 6-199; key features of the Allt Mòr section/Member are illustrated in Figure 6-200, Figure 6-201, Figure 6-202, Figure 6-203, Figure 6-204 and Figure 6-205. Clast lithologies within the conglomerates, mainly rounded to sub-rounded cobbles and pebbles, are of distinctive orange-brown Torridonian Supergroup quartz arenite (sandstone) and laminated siltstone, pale biotite and pyroxene-hornblende granophyric-textured granite, together with relatively rare quartz-porphyritic felsite. Given the relatively resistant-to-erosion character of all of these lithologies, it is evident that these clasts have been subjected to significant transport. The granite clasts match well with the Western Granite/Granophyre on Rum (Chapter 9), which pre-dates the lavas on Rum that are a southern extension of the Skye Lava Field (see below). The felsite clasts do not have such a similarly good correspondence/match with the felsites that crop out on Rum, which are interpreted as ignimbrites (Bell & Emeleus 1988) (Chapter 9).

Sedimentary units on Rum belonging to the Torridonian sequence and acting as the dominant country-rock to the Rum Central Complex (Chapter 9), match well the sedimentary clasts within the Minginish Conglomerate Formation. Clasts of basalt, hawaiite and mugearite are present, but are rare. Thus, a southerly source for the Minginish Conglomerate Formation clasts can be inferred (Williamson & Bell 1994).

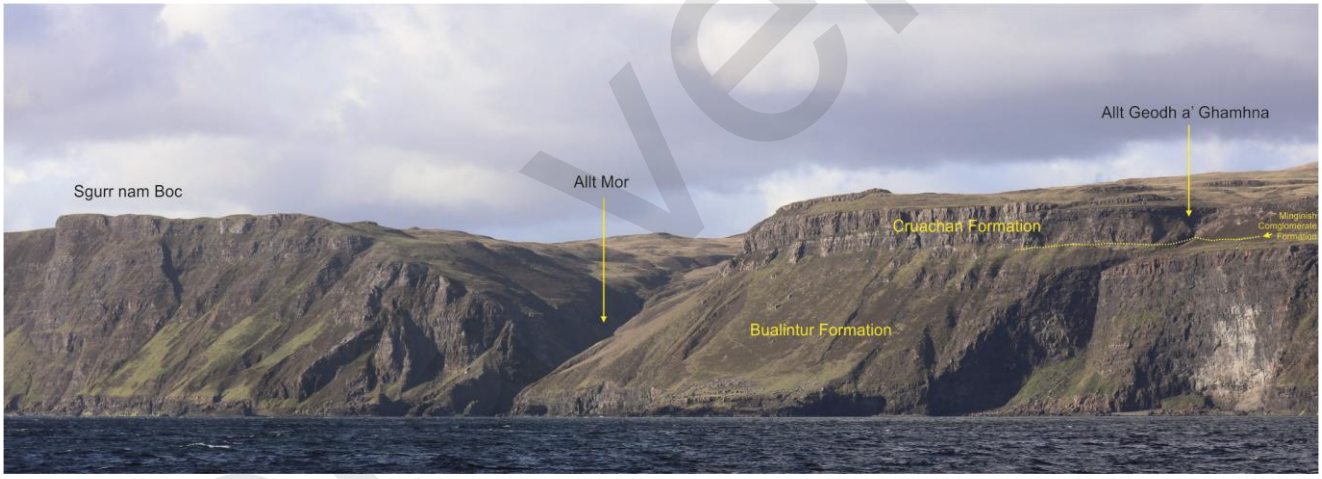


Figure 6-196: Coastal section between Sgùrr nam Boc and the Allt Geodh a' Ghamhna, between lochs Eynort and Brittle, Minginish, composed of lavas of the Bualintur and Cruachan formations. The sedimentary unit between the two formations, the Minginish Conglomerate Formation, exposed between the Allt Mor and the Allt Geodh a' Ghamhna, indicated by the dashed line.

Boo version



Figure 6-197: Location of the Allt Geodh a' Ghàmhna Member (arrowed) of the Minginish Conglomerate Formation in the vicinity of the Allt Geodh a' Ghàmhna, Minginish.



Figure 6-198: Field view of the Allt Geodh a' Ghàmhna Member of the Minginish Conglomerate Formation, with matrix-supported conglomerates forming prominent, resistant-to-erosion ribs, on the east bank of the Allt Geodh a' Ghàmhna.

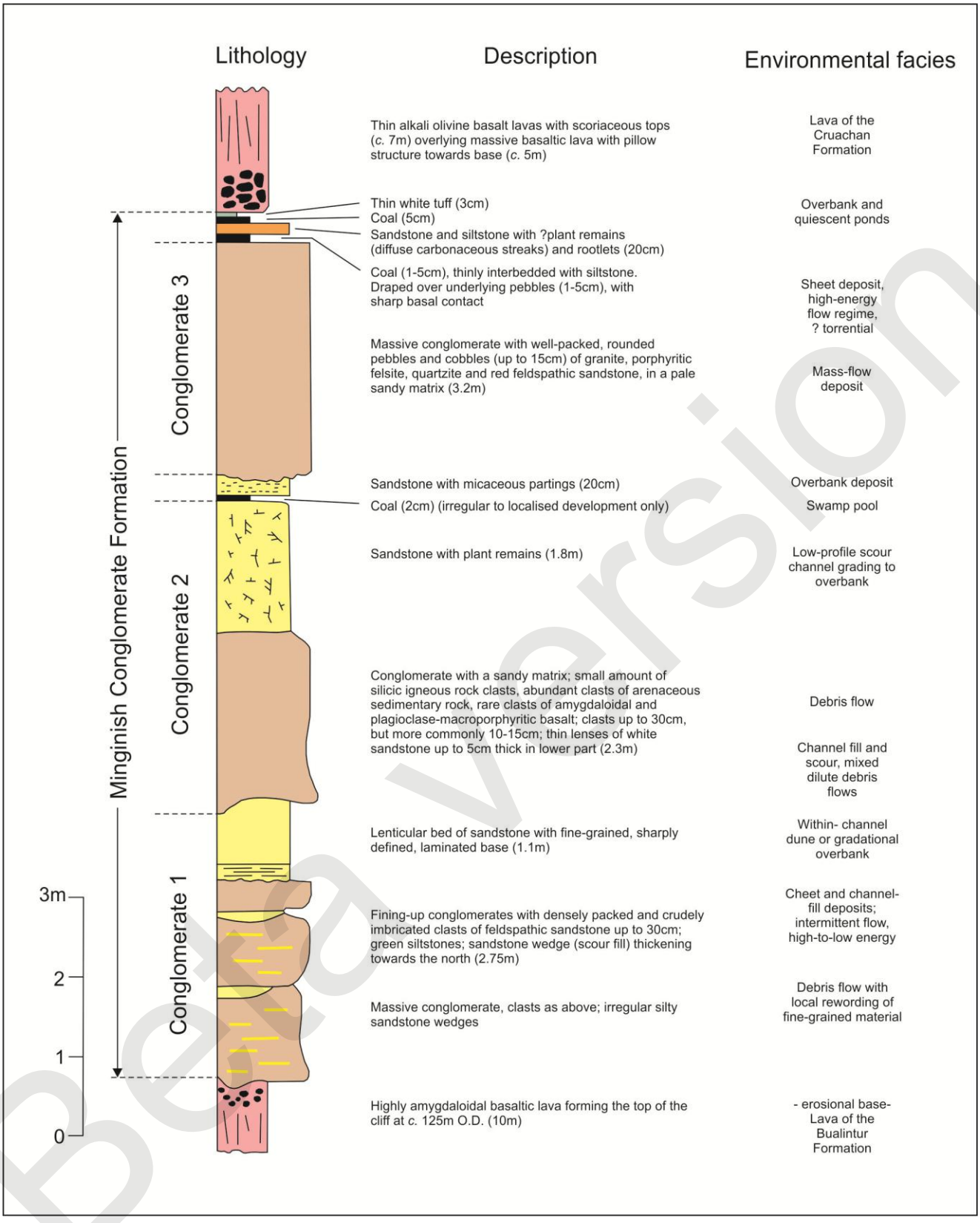


Figure 6-199: Stratigraphical section for the Allt Geodh a' Ghàmhna Member of the Minginish Conglomerate Formation (based on Williamson & Bell 1994).

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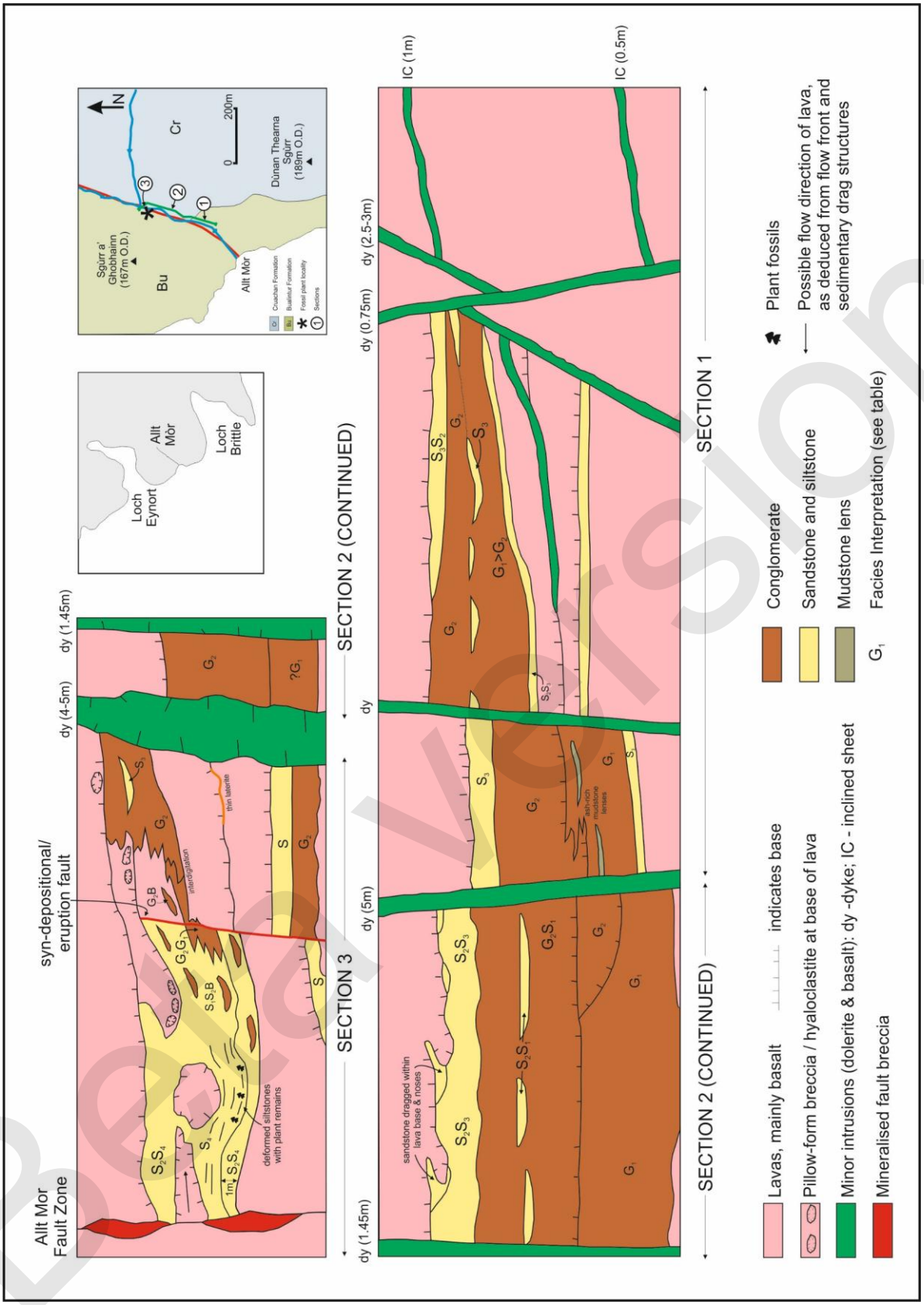


Figure 6-200: Schematic sections (not to scale) within the Allt Mòr Member of the Minginish Conglomerate Formation, Allt Mòr, Minginish (based on Williamson & Bell 1994).

Beta version



Figure 6-201: Field view of lava lobe within Section 3 (see Figure 6.187), Allt Mòr Member, Minginish Conglomerate Formation, Minginish, Skye.



Figure 6-202: G2 clast-supported conglomerate in the Allt Mòr Member, Allt Mòr section, Minginish, Skye. Person for scale.

Proof version



Figure 6-203: Detail of G2 clast supported conglomerate in the Allt Mòr Member, Allt Mòr section, Minginish, Skye. Pole *ca*. 1 m long.



Figure 6-204: Detail of G2 clast supported conglomerate) in the Allt Mòr Member, Allt Mòr section, Minginish, Skye, with dominant orange-brown clasts of Torridonian sandstone and pale Paleocene granite. Coin *ca*. 24 mm across.

Code	Facies	Sedimentary structures	Interpretation
G1	Matrix-supported conglomerate	Massive to crudely-graded	Debris flow deposit
G2	Clast-supported conglomerate	**A:** weakly stratified, planar, normally-graded, locally imbricate **B:** Lenticular, trough cross-bedded	Sheet deposit or longitudinal bar Channel fill or scour
S1	Pebbly, silty coarse-grained sandstone	Massive	Dilute debris flow or avalanche deposit
S2	Fine- to coarse-grained, locally pebbly, sandstone	**A:** Trough cross-bedded, pebbles at base of troughs **B:** Trough cross-bedded, upper surfaces rippled, graded profiles	Within-channel dunes and lag deposits Within-channel dunes and channel fill and scour
S3	Fine- to medium-grained, silty sandstone	Planar cross-bedded	Linguoid and transverse bar or low-angle scour fills
S4		Massive to faintly sub-parallel laminated; plant remains	Channel infilling, relative quiescence, locally lacustrine
S5	Interbedded siltstones and mudstones	Thinly bedded to coarse inter-laminated; horizontal to wavy laminations	Similar to overbank deposits, but could be upper flow regime (waning current)
C	Coal	**A:** Bright, massive **B:** Dull to banded	Allocthonous, washed-in plant (mainly woody) remains Autochthonous,*in situ* vegetation; swamp/mire conditions

Figure 6-205: Details of sedimentary facies and structures within the Allt Mòr Member, Allt Mòr section, Minginish, Skye (based on Williamson & Bell 1994).

The overlying Cruachan Formation is separated from the Rubha an Dunain and Bualintur formations by the laterally discontinuous Minginish Conglomerate Formation. The Cruachan Formation (Figure 6-206) is subdivided into two members, the Glen Brittle and An Crocan members, both dominated by interbedded basalt and hawaiite lavas. A single picritic basalt lava occurs in the Glen Brittle Member on An Cruachan (Bell & Williamson 1994).

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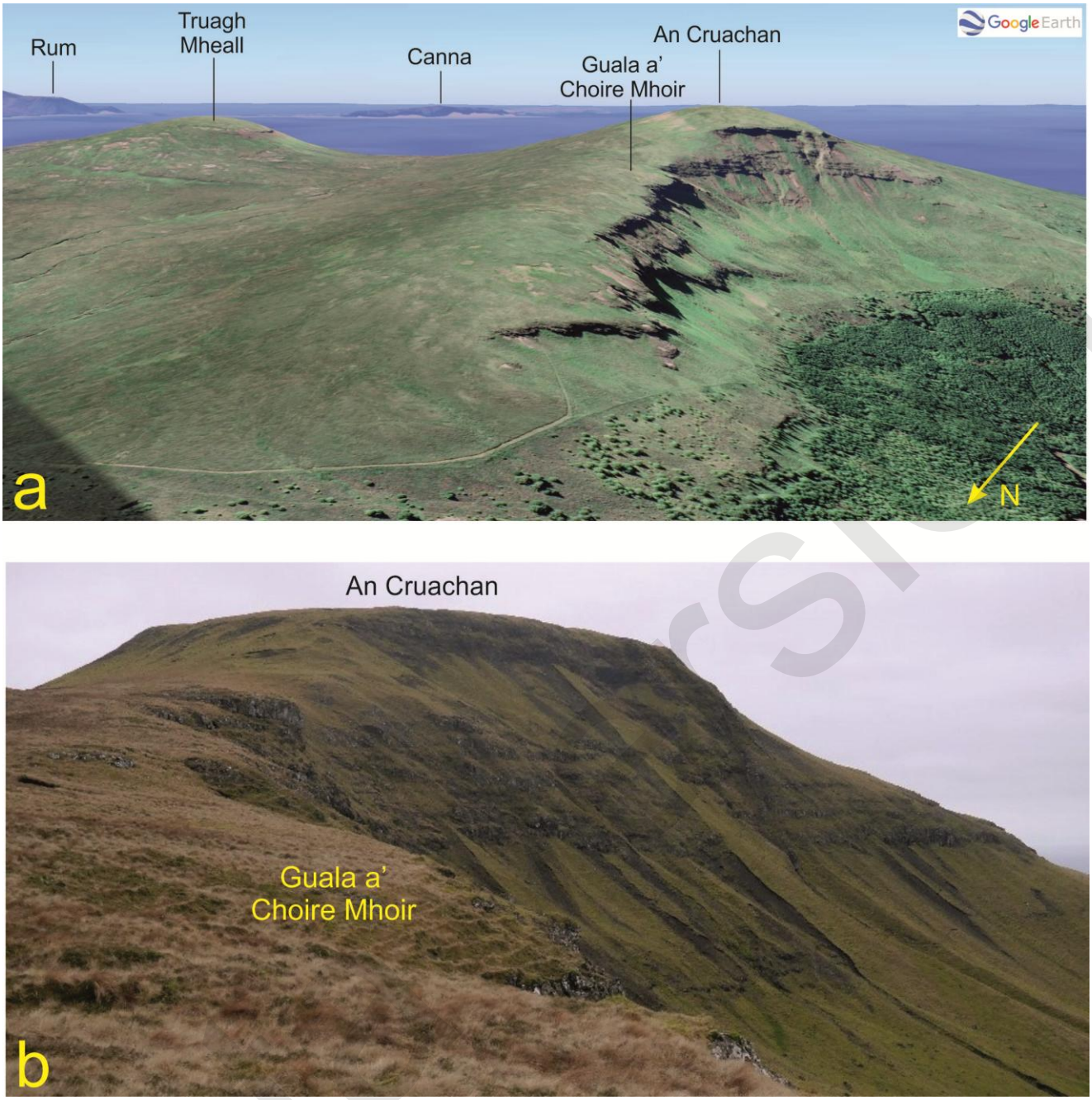


Figure 6-206: (a) Oblique Google Earth© image of An Cruachan and Truagh Mheall, composed of Cruachan Formation (Glen Brittle Member) interbedded basalt and hawaiite lavas; and, (b) field view of An Cruachan and the crags of Guala a' Choire Mhoir, view towards the south.

The Glen Caladale Formation is interpreted to be younger than the previously described sequences (Figure 6-193), although precise field relationships are not clear, mainly due to relatively poor exposure in the area around Loch Eynort. Four members are identified: Tusdale (oldest), Stac a' Mheadais, Sgùrr Buidhe and Skridan (youngest). Simple sheet and compound lavas of basalt, hawaiite and mugearite dominate, with olivine and plagioclase porphyritic variants being relatively common. A picritic basalt lava occurs towards the base of the Tusdale Member between Sgùrr Mòr and Sgùrr Beag. The Stac a' Mheadais Member is represented by a single sheet-like mugearite lava up to 25 m thick and prominently cropping out on the sea-cliff opposite Stac a' Mheadais (Figure 6-207). It overlies a distinctive red-brown laterite, has a brecciated, lateritised top and forms substantial inland exposures. The Stac a' Mheadais Member is overlain, locally, by thin sandstones, siltstones and mudstones, above which are simple and compound

basalt and hawaiite lavas of the Sgùrr Buidhe Member. The hawaiite lavas can be traced from the sea cliffs where they crop out near Stac a' Mheadais, inland, forming bold escarpments between Glen Caladale and Tusdale, apparently terminating SE of Beinn na Cuinneig. The Skridan Member is dominated by compound olivine basalt lavas and, traced along the sea cliffs NW towards Talisker Bay, appear to interdigitate with lavas of the (younger) Fiskavaig Formation.



Figure 6-207: The Glen Caladale Formation in the coastal section below Sgùrr Buidhe, with amygdaloidal basaltic and hawaiitic lavas of the Sgùrr Buidhe Member, overlying a thick prismatic-jointed mugearite lava at the base of the cliff and on the islet of Stac a' Mheadais. View towards the SE.

Superb exposures of inflated pahoehoe (compound) lavas of the Glen Caladale Formation crop out on the south side of Talisker Bay, at Talisker Point, forming the tidal islet of An Stac and the adjacent coastal cliffs (Figure 6-208; Figure 6-209; Figure 6-210; Figure 6-211; Figure 6-212; Figure 6-213; Figure 6-214; Figure 6-215; Figure 6-216; Figure 6-217; Figure 6-218; Figure 6-219).

Beta version



Figure 6-208: The main (east) face (landward side) of An Stac. Height of the main face is *ca.* 18 m, with a further *ca.* 5 m forming the central top. Detailed observations are restricted to the main face and the lowest part of the central top. The most conspicuous feature of the main face of basaltic lava(s) is the distinctive red-orange-brown layers, which are rubbly top facies. The four coloured layers suggest four discrete lavas: however, more detailed examination suggests that this interpretation is not correct (see figures below). A brown-weathering, jointed, basaltic inclined sheet cuts the sequence on the north (right) side of the face. Iain Allison for scale.



Figure 6-209: Detail of the east side of the top of An Stac.

Beta version



Figure 6-210: Inclined intrusive sheet, most obvious where in contact with reddened rubbly (lava) top facies on the main east (landward) side of An Stac.



Figure 6-211: East (left) side of An Stac with thin sheet facies of pahoehoe lava at the accessible base of crag; a thicker sheet forms the top of the crag, above and below which are intervals of similar reddened, brecciated lava.

Beta version



Figure 6-212: South side of An Stac, with: thin sheet facies of pahoehoe lava at the accessible base of crag; a thicker sheet forms the top of the crag, above and below which are intervals of reddened, brecciated lava.



Figure 6-213: South (left) side of An Stac with thin sheet facies of pahoehoe lava. Pole *ca*. 1 m long.



Figure 6-214: Detail of sheet facies on the east face of An Stac. Note: sharp sheet-sheet contacts whereby the order of development ('emplacement') can be determined; amygdale-rich intervals parallel to the margins of individual sheets; and, minor reddening of fine-grained margins of sheets. Pole *ca.* 1 m long.



Figure 6-215: Detail of banded lava facies on the east face of An Stac. Note: sharp sheet-sheet contacts whereby the order of development ('emplacement') can be determined; amygdale-rich intervals parallel to the margins of individual sheets; and, minor reddening of fine-grained margins of sheets. Pole *ca.* 1 m long.



Figure 6-216: Pahoehoe (compound) lava (Hawai'i; USGS public domain) during its growth, with countless thin, irregular, sheet-like lobes with complex geometries, including the formation of voids and ropy upper surfaces. Recognisable and preservable sheet-sheet contacts form, with individual sheets commonly being vesicular (and amygdaloidal after burial and the ingress of mineral-rich heated groundwater through the lava sequence).



Figure 6-217: The reddened brecciated lava facies at the top of the platform on the south side of An Stac. Pole *ca.* 1m long.



Figure 6-218: Detail of the reddened brecciated lava facies at the top of the platform on the south side of An Stac, with angular fragments of amygdaloidal basalt, some over 10 cm across. The reddening is particularly well developed in the finer-grained material. Coin *ca.* 24 mm across.



Figure 6-219: Invasive lobe (centre right) of basalt into reddened brecciated lava facies, indicating that the lava has developed by multiple 'injection' or 'intrusion' events and that each layer of reddened brecciated lava seen in section view need not necessarily indicate the top of a lava formed by a discrete eruption event. Pole *ca.* 1 m long.



Figure 6-220: Large gas cavities partially filled with hydrothermal minerals. The left-hand cavity is coated by prismatic crystals and the right-hand by delicate acicular crystals. Both minerals are members of the zeolite family (not determined). Coin *ca*. 24 mm across.

The Fiskavaig Formation, comprising the McFarlane's Rock and Rubha nan Clach members, crops out over a significant area north of Gleann Oraid, as far as Loch Bracadale and Loch Harport, and interdigitates with the upper part of the Glen Caladale Formation. The lower of the two members, the McFarlane's Rock Member, comprises compound basalt lavas, a prominent, prismatic-jointed mugearite, and hawaiite lavas with distinctive red-brown lateritic tops, best seen in the cliffs on the north side of Talisker Bay (Figure 6-221; Figure 6-222; Figure 6-223; Figure 6-224). The McFarlane's Rock Member is particularly well exposed at Rubha Cruinn, on the north side of Talisker Bay. The most spectacular of the evolved lavas is the mugearite that crops out on McFarlane's Rock and along the adjacent coastline, and which has very well developed flow bands with complex fold patterns (Figure 6-225; Figure 6-226). The overlying Rubha nan Clach Member comprises interbedded compound basalt lavas and laterally extensive sheet hawaiite lavas.

Beta version



Figure 6-221: Fiskavaig Formation strata forming the north side of Talisker Bay, Minginish, Skye. The sequence comprises mainly basaltic and hawaiitic lavas of the Rubha nan Clach Member overlying the thick, flow-banded mugearite lava of the McFarlane's Rock Member (at the base of the cliff) with an obvious lateritic top. Height of cliff *ca.* 120 m.

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Figure 6-222: Detail of Fiskavaig Formation strata on the north side of Talisker Bay, Minginish, Skye, comprising thin sheet basaltic lavas, many with lateritised (reddened) tops (palaeosols).

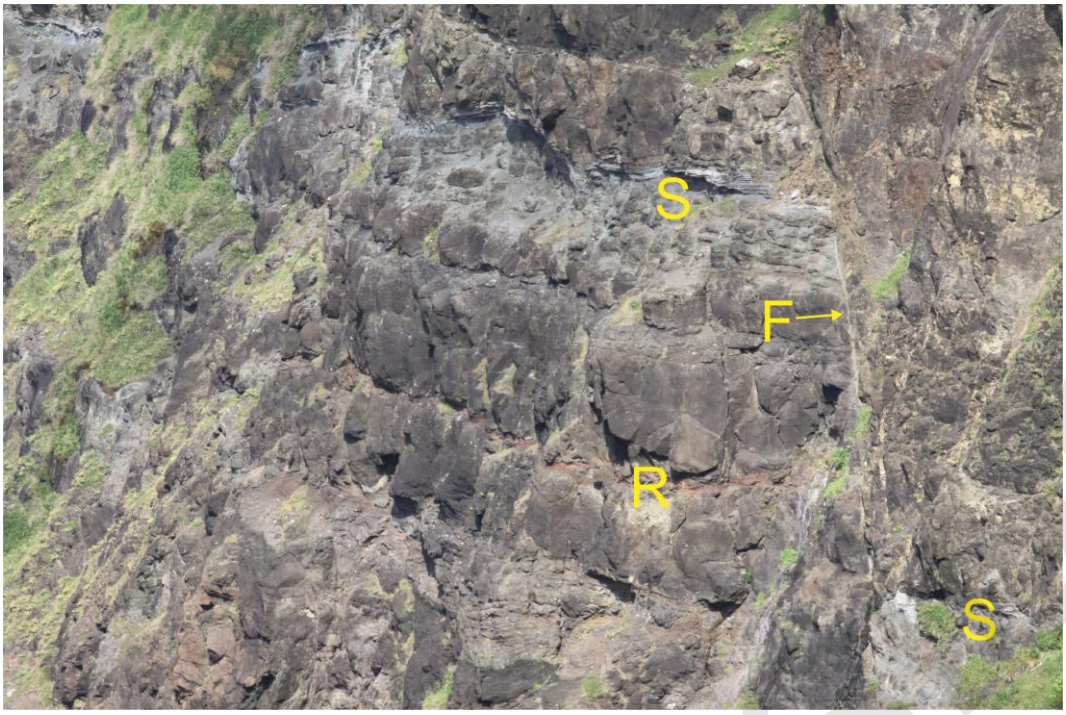


Figure 6-223: Detail of Fiskavaig Formation strata on the north side of Talisker Bay, Minginish, Skye, comprising thin sheet flows, many with lateritised (reddened) tops (palaeosols) (R) and thin sedimentary units (S). Note fault, F, with throw indicated by the relative displacement of the pale grey, laminated sedimentary unit.



Figure 6-224: Detail of Fiskavaig Formation strata forming the promontory of Rubha Cruinn on the north side of Talisker Bay. The sequence comprises mainly basaltic and hawaiitic lavas of the Rubha nan Clach Member overlying the thick, flow-banded mugearite lava of the McFarlane's Rock Member with an obvious lateritic top (palaeosol).

Beta version



Figure 6-225: (Flow-) banded mugearite lava in the McFarlane's Rock Member at McFarlane's Rock on the north side of Talisker Bay. Ruler 30 cm long.



Figure 6-226: (Flow-) banded mugearite lava in the McFarlane's Rock Member at McFarlane's Rock on the north side of Talisker Bay. Ruler 30 cm long.

The overlying Eynort Mudstone Formation, stratigraphically above the Rubha nan Clach Member in the area around Rubha nan Clach, but also stratigraphically above the Skridan Member of the Glen Caladale Formation in the area around Beinn Bhreac, was deposited after a prolonged period of intense weathering and erosion, followed by deposition of fine-grained sediment in a lacustrine setting. These siltstones and mudstones contain abundant volcanic material and are variably interbedded with carbonaceous shales, ironstones and impure lignitic coals. Exposures occur on Ben Scaalan, on Biod Mòr, in Gleann Oraid on the slopes of Arnaval and Stockval facing the glen, and on the southern slopes of Beinn nan Dubh-lochan above Loch an Sgùirr Mhòir. Four members are recognised (based upon locally developed sequences: the Ben Scaalan Member, the Biod Mòr Member, the Gleann Oraid Member, and the Loch an Sgùirr Mhòir Member (Williamson & Bell 1994). An easily accessed sequence is exposed in the Carbost Burn, south of the Talisker Distillery at Carbost, below a thick, sheet-like mugearite lava (Figure 6-227).



Figure 6-227: A thick mugearite lava of the Glean Oraid Formation overlying the sedimentary sequence of the Eynort Mudstone Formation in the Carbost Burn, SW of Carbost, Minginish, Skye.

The overlying Gleann Oraid and Loch Dubh formations interdigitate in the area around Beinn nan Dubh-lochan and Loch Dubh. The Gleann Oraid Formation consists of three members, Arnaval (oldest), Sleadale and Cnoc Scarall (youngest?), and is dominated by relatively evolved lavas, hawaiites, mugearites and benmoreites, which form prominent summits and ridges, for example, Na Huranan, SE of Arnaval (Figure 6-228; Figure 6-229). Interbedded with these lavas, many with well-developed flow structure/banding, are compound basalt lavas. A single benmoreite lava forms the two hills, Cnoc Dubh Heilla and Cnoc Glas Heilla, south of Portnalong. The base of the Gleann Oraid Formation is not planar, and the initial lavas of the sequence appear to have ponded in depressions on the palaeo- land surface.



Figure 6-228: Hawaiite and mugearite lavas of the Arnaval Member of the Gleann Oraid Formation, forming the summit area of Arnaval (centre) and the Na Huranan crags (right) on the north side of Gleann Oraid. View towards the north.



Figure 6-229: Planar fabric, locally folded (right of hammer) in an hawaiite lava, south side of Arnaval, Gleann Oraid, Minginish, west-central Skye. Hammer *ca*. 30 cm long.

The Sleadale Member is represented by two units, a distinctive red-brown, lateritised trachyte tuff, up to 3 m thick, with remarkably fresh anorthoclase and biotite crystals, overlain by a thick, vesicular porphyritic trachyte lava (Bell & Williamson 2013). The tuff crops out only NW of Preshal Beg on the south side of Sleadale, whereas the trachyte lava occurs both north of Preshal Beg and to the SE of Preshal More on the north side of Sleadale (Figure 6-230).

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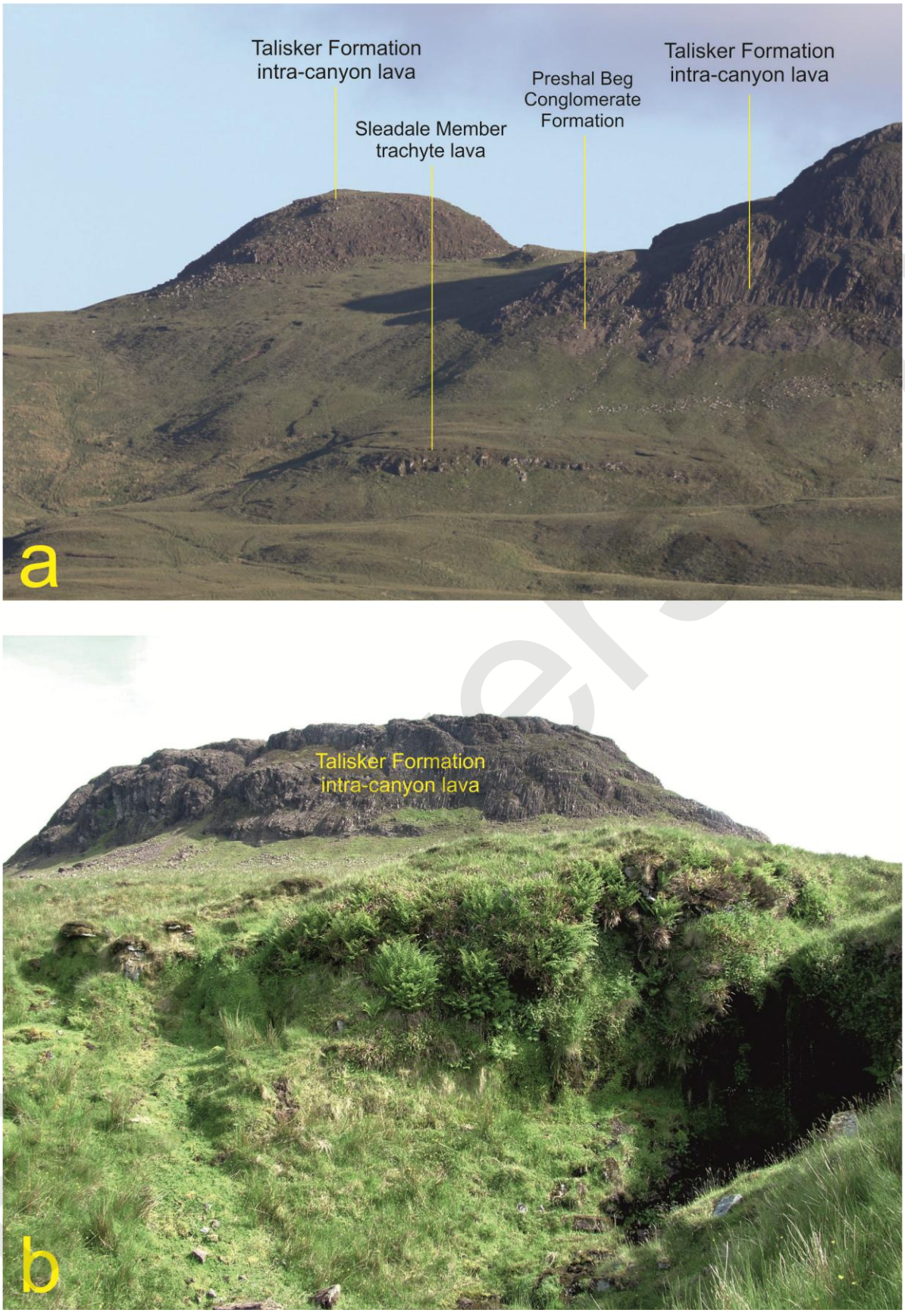


Figure 6-230: (a) Sleadale Member (Gleann Oraid Formation) trachyte lava forming a distinct terrace (bottom central) on the north side of Preshal Beg (top right), Minginish, view towards the SE; (b) poorly exposed trachyte tuff, NE of Preshal Beg.

The Cnoc Scarall Member is an isolated, ponded, compound lava, at least 100 m thick, of porphyritic trachyte. It is located on the east side of Glen Eynort, forming the twin summits of Cnoc Scarall (Figure 6-231), and overlies both the Arnaval Member of the Gleann Oraid Formation and the Skridan Member of the Glen Caladale Formation.



Figure 6-231: Trachyte lava, Cnoc Scarall, Glen Eynort, Minginish, west-central Skye.

The Loch Dubh Formation, interdigitated with the Gleann Oraid Formation, comprises interbedded plagioclase-micro-porphyritic basalt and hawaiite lavas, together with a plagioclase-macro-porphyritic hawaiite lava that forms the broch-capped hill, Dùn Ard an t-Sabhail (Figure 6-232; Figure 6-233).



Figure 6-232: Plagioclase-macro-porphyritic hawaiite lava forming the broch-capped hill, Dùn Ard an t-Sabhail, Minginish, SW Skye. View SE towards Arnaval (in sunlight).

Pre-publication version



Figure 6-233: Plagioclase macro-porphyritic basaltic lava, Dùn Ard an t-Sabhail, Minginish, west-central Skye. Coin *ca.* 24 mm across.

A major hiatus in the volcanism occurred after the eruption of the main plateau-building sequence (Bell & Williamson 2013). The next preserved unit, the Preshal Beg Conglomerate Formation, was deposited locally in a steep-sided valley, or canyon, drainage system, carved out of the pre-existing plateau lava landscape. It consists of various coarse-grained sedimentary units, poorly sorted and typically unstratified breccias and conglomerates, of debris flow and fluvial channel association, together with fluvial channel and overbank sandstones, siltstones and mudstones (Figure 6-234; Figure 6-235; Figure 6-236; Figure 6-237; Figure 6-238; Figure 6-239; Figure 6-240). All are volcaniclastic in character, essentially devoid of siliciclastic material. Outcrops are restricted to the flanks of the twin summits of Preshal More and Preshal Beg, SE of Talisker Bay, in particular the NE side of Preshal Beg (Figure 6-237). Unlike the conglomerates of the Minginish Conglomerate Formation, the cobbles and pebbles are of local derivation and are solely of lava field lithologies, mainly basalt, hawaiite and mugearite, together with their scoriaceous and amygdaloidal variants.



Figure 6-234: The two outliers of the Talisker Formation, forming Preshal More (near, left) and Preshal Beg (far, right), overlying the Preshal Beg Conglomerate Formation, south of Gleann Oraid, Minginish.

Beta version



Figure 6-235: The prominent Preshal More outcrop of the Talisker Formation on the south side of Gleann Oraid, overlying (behind) lavas of the Gleann Oraid Formation on Stockval. In the distance, in cloud, is the Cuillin.



Figure 6-236: Preshal More on the south side of Gleann Oraid, forming one of the two outliers of tholeiitic basalt lava of the Talisker Formation. In the foreground, the sea cliffs comprise basalt and mugearite compound and simple lavas of the Glen Caladale Formation.

Book version



Figure 6-237: Preshal Beg Conglomerate Formation on the NE side of Preshal Beg, comprising a very poorly sorted, unlayered, pebble to boulder conglomerate. Ian Williamson for scale.



Figure 6-238: Preshal Beg Conglomerate on the south side of the small satellite hill east of Preshal Beg, comprising volcaniclastic sandstones with interbeds of pebbly sandstone and pebble conglomerate. Pole *ca.* 1 m long.

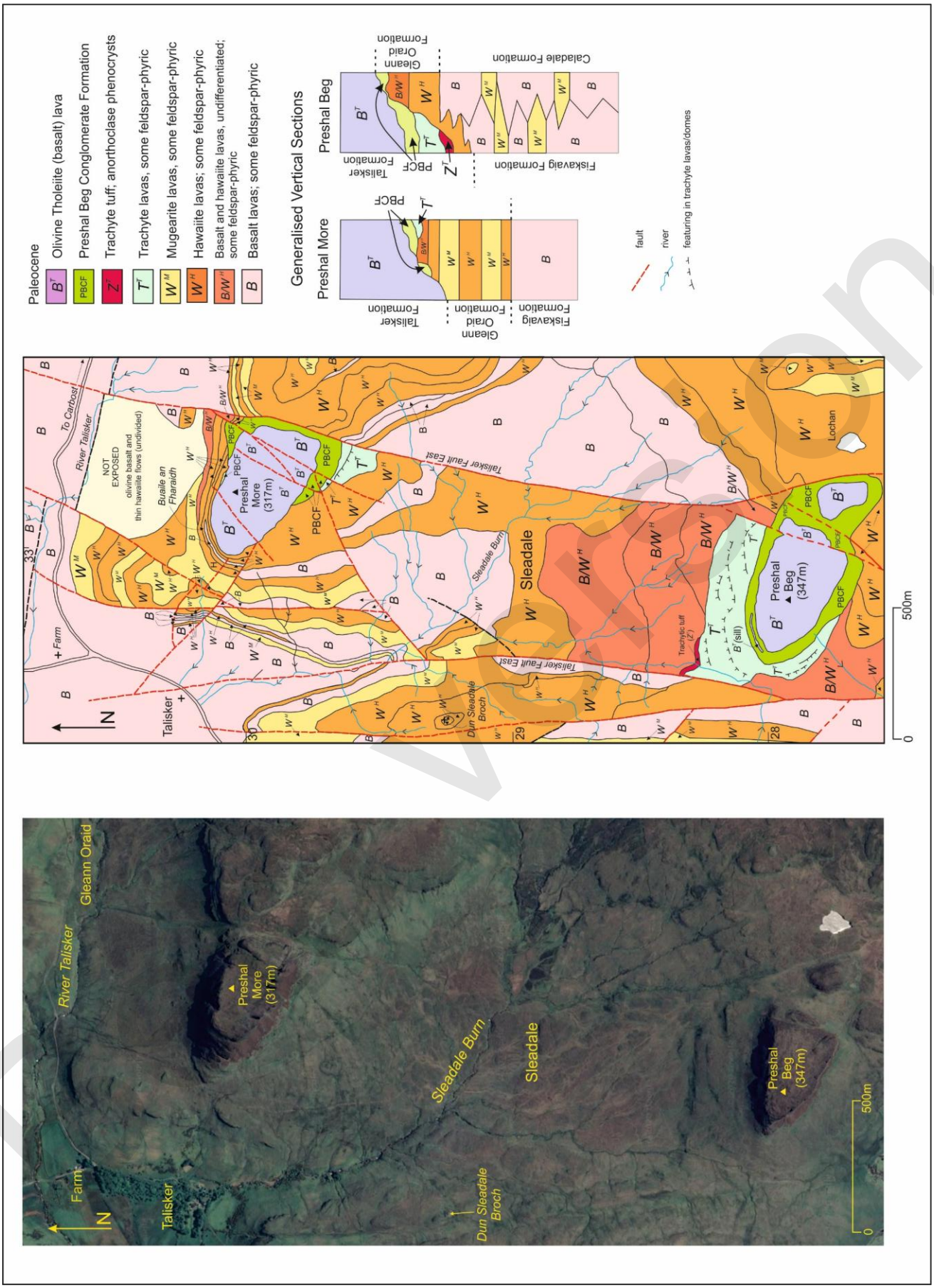


Figure 6-239: Detailed geological map of the Preshal More – Preshal Beg area, Minginish (after Bell & Williamson 2013).

Preview version

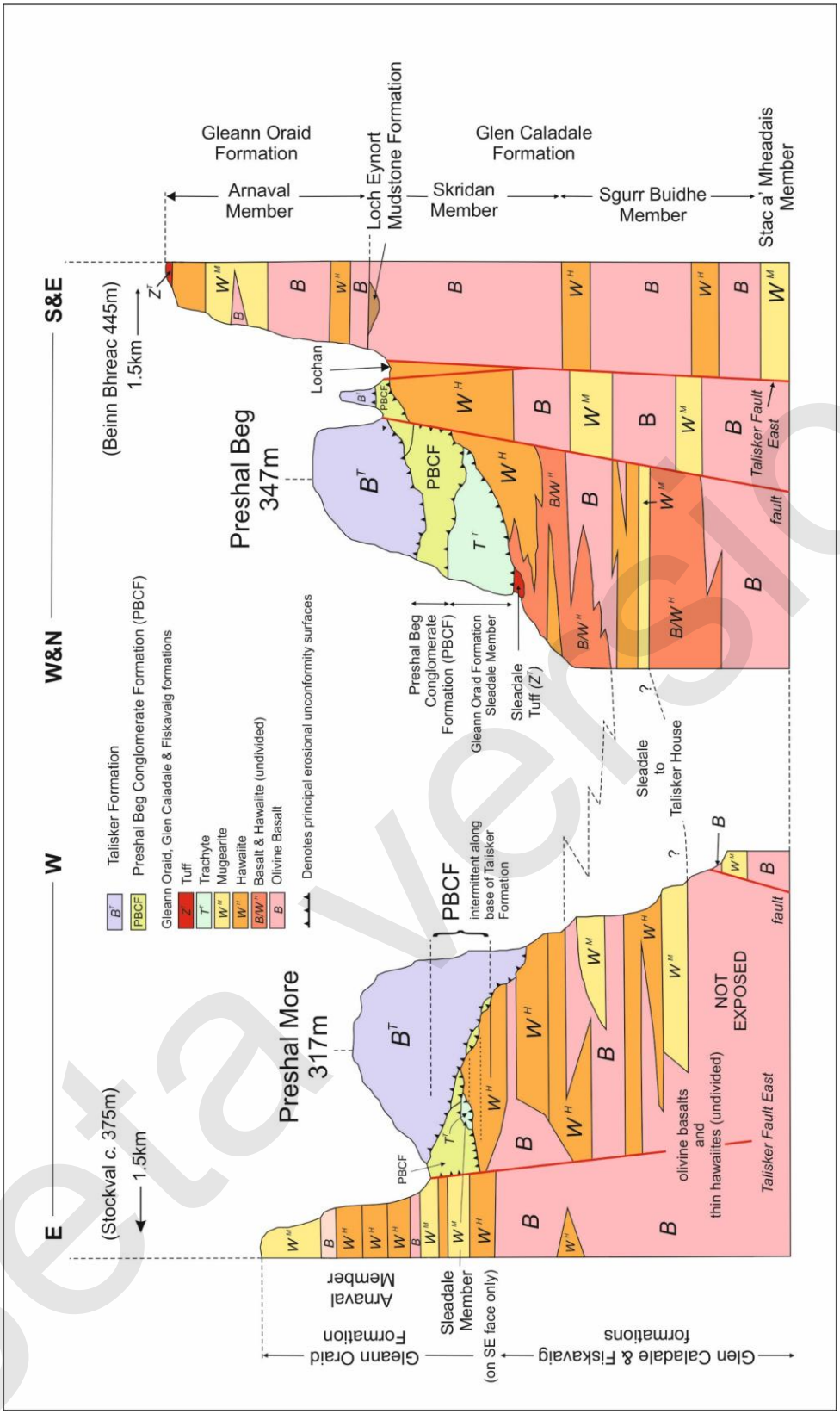


Figure 6-240: Schematic geological cross-section of the Preshal More – Preshal Beg area, Minginish, illustrating general stratigraphic and structural relationships of the Talisker Formation lava (after Bell & Williamson 2013). Vertical and horizontal scales differ.

The drainage system was then inundated by the intra-canyon tholeiitic basalt Talisker Formation lava, which has a thickness of at least 120 m. The basal part of the lava has both pillowed and hyaloclastite facies (Figure 6-241; Figure 6-242), indicative of eruption into water.

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Figure 6-241: Basalt pillows in hyaloclastite at the base of the Talisker Formation lava, south side of the Preshal Beg outcrop, Minginish. Ruler 30 cm long.



Figure 6-242: Inclined columns of the colonnade of the Talisker Formation lava in contact with hyaloclastite (pale weathered), produced by magma-water interaction during the initial stages of the eruption. North face of Preshal More, Minginish.

Differential weathering and erosion have led to a topography inversion, whereby the more resistant (to erosion) canyon-filling lava now forms the high ground and the relatively less resistant valley-wall lavas of the older plateau sequence form the present-day lower ground of Sleadale. The main subdivisions of the lava are best illustrated on the Preshal Beg outcrop (Figure 6-243).

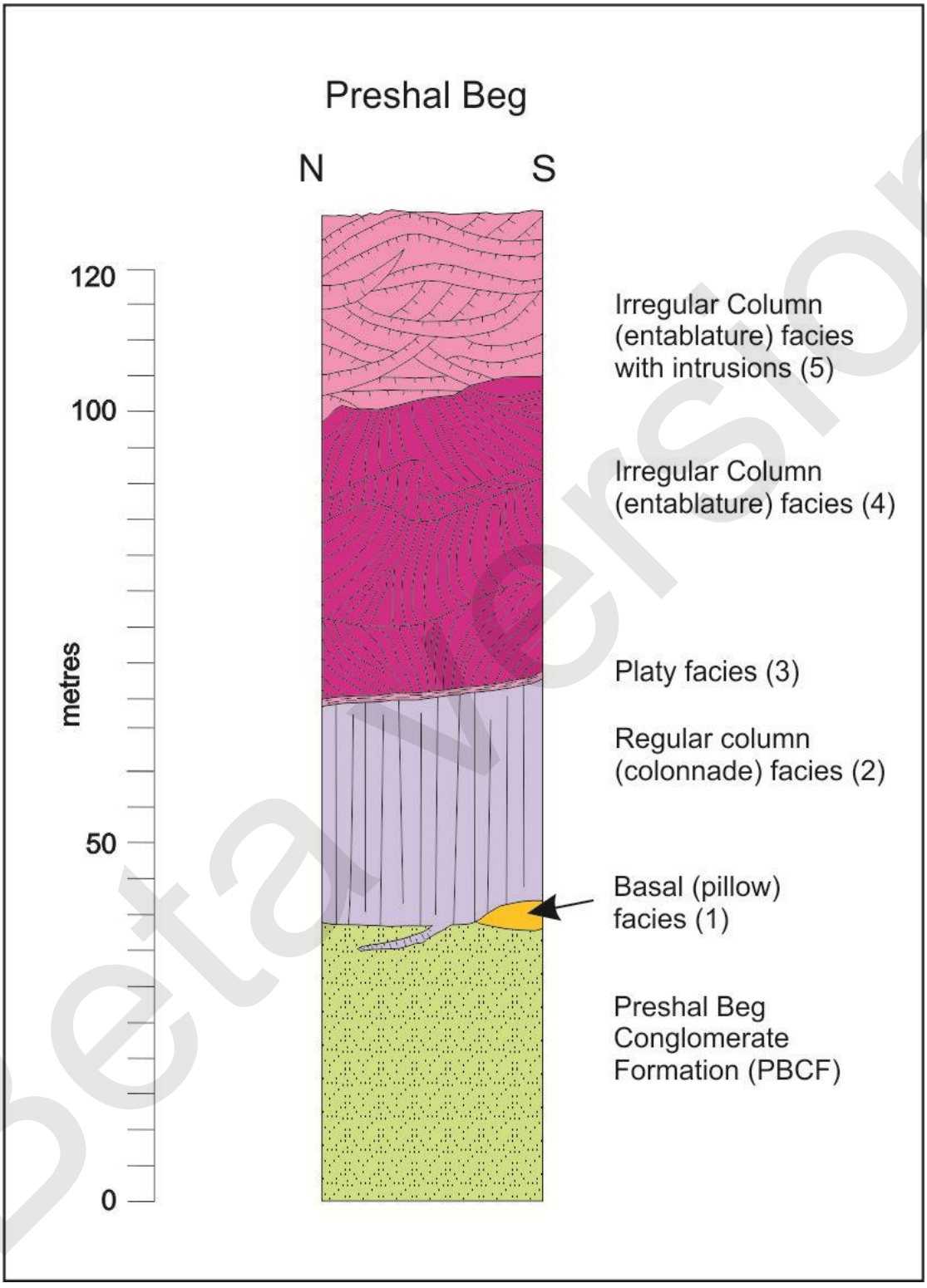


Figure 6-243: Main sub-units of the intra-canyon Talisker Formation lava on Preshal Beg, Minginish, west-central Skye.

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The two main outcrops, forming the spectacular summits of Preshal More (Figure 6-244; Figure 6-245) and Preshal Beg (Figure 6-246; Figure 6-247; Figure 6-248), have significant colonnades defined by hexagonal-patterned columnar joints, above which are entablatures comprising less regular joint patterns (Figure 6-247). The transition between the two styles of joints is abrupt, with a thin intervening platy facies. On Preshal Beg, especially obvious on the south side of the hill, the entablature exhibits an intrusive/sheeted facies (Figure 6-247; Figure 6-248).



Figure 6-244: Colonnade and entablature on the south side of the Preshal More outcrop of the Talisker Formation lava, Minginish, west-central Skye.



Figure 6-245: Colonnade and entablature on the south side of the Preshal More outcrop of the Talisker Formation lava, Minginish, west-central Skye.

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Figure 6-246: Preshal Beg on the south side of Sleadale, forming one of the two outliers of tholeiitic basalt lava of the Talisker Formation. In the foreground, the sea cliffs comprise basalt and mugearite compound and simple lavas of the Glen Caladale Formation and the (overlying) Glen Oraid Formation.

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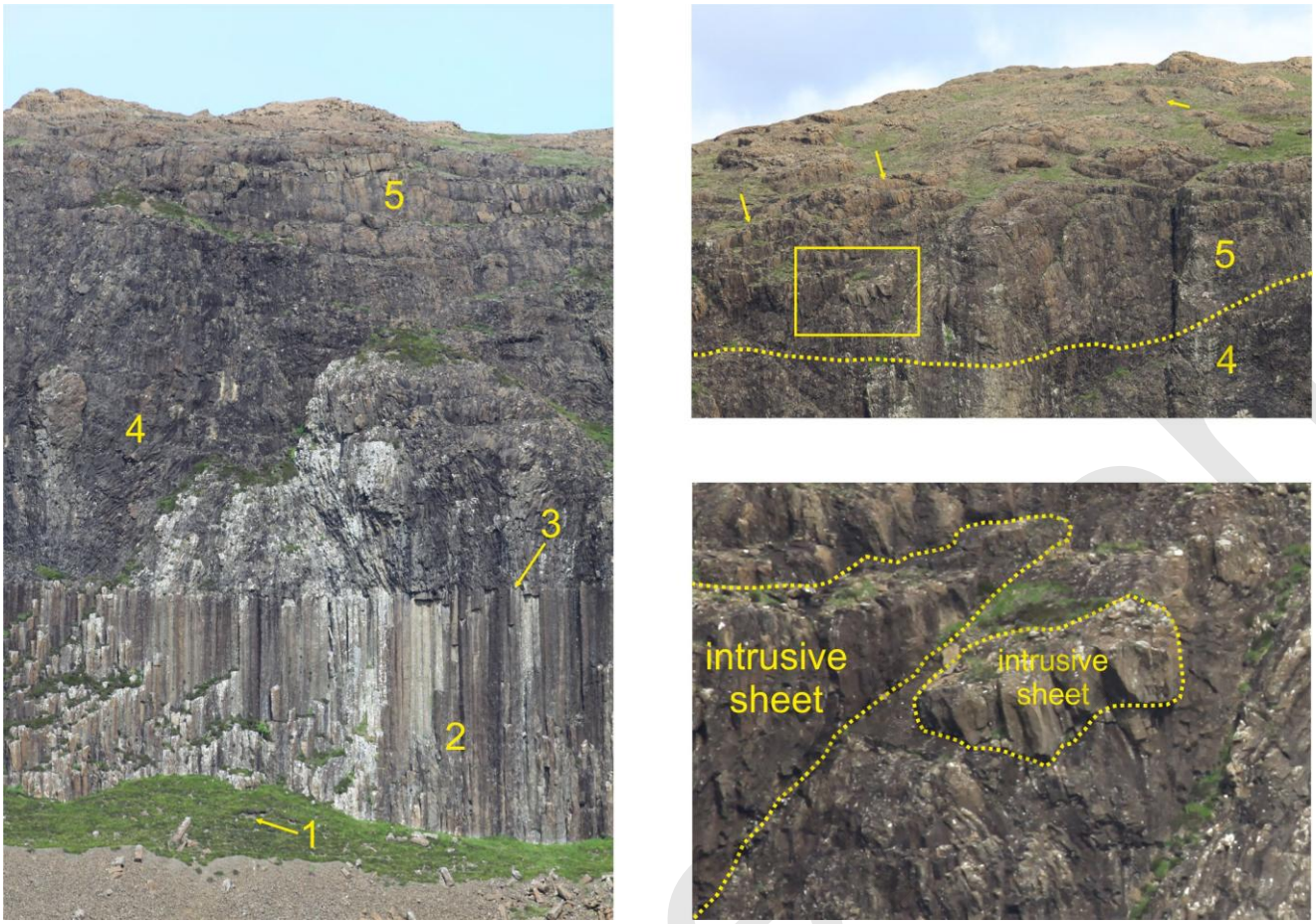


Figure 6-247: Annotated views of the south side of Preshal Beg. Vertical extent of lava outcrop is *ca.* 120 m. See caption of Figure 6.220 for details of numbered features. 1: basal (pillow) facies; 2: colonnade; 3: platy facies; 4: entablature; 5: entablature with intrusive sheets.



Figure 6-248: South face of Preshal Beg, illustrating the main sub-units (see Figure 6.220) of the intra-canyon Talisker Formation lava that forms the twin summits of Preshal More and Preshal Beg. View towards the north. 1: basal (pillow) facies; 2: colonnade; 3: platy facies; 4: entablature; 5: entablature with intrusive sheets.

The top of the lava is not preserved, although the flat summit area of Preshal Beg gives excellent access to the intrusive/sheeted facies of the lava (Figure 6-247; Figure 6-248), interpreted as being relatively close to the original top of the lava.

The composition of the Talisker Lava is significantly different from the transitional to mildly alkaline basalt lavas that occur within the volumetrically dominant underlying sequence (Chapter 10). It is of tholeiitic basalt composition, very similar to that of Mid Ocean Ridge Basalt (MORB) and, importantly, similar in composition to a significant proportion of the dykes of the Skye Main Dyke Swarm (Chapter 7) and the cone-sheets that intrude the various coarse-grained intrusions of the Cuillin Intrusive Centre (Chapter 9). Bell & Williamson (2013) propose that the Talisker Lava was sourced from a Cuillin Volcano (Chapter 9), the superstructure of which has been removed by erosion since the end of the volcanism (Figure 6-249). The original extent of the lava is unknown, although the location of Preshal More and Preshal Beg, *ca.* 15 km distant from the Cuillin Intrusive Centre, indicates a minimum drainage path length, and which is very conservative, given that the nearby coastline is fringed with high cliffs composed of the older plateau lava sequence.

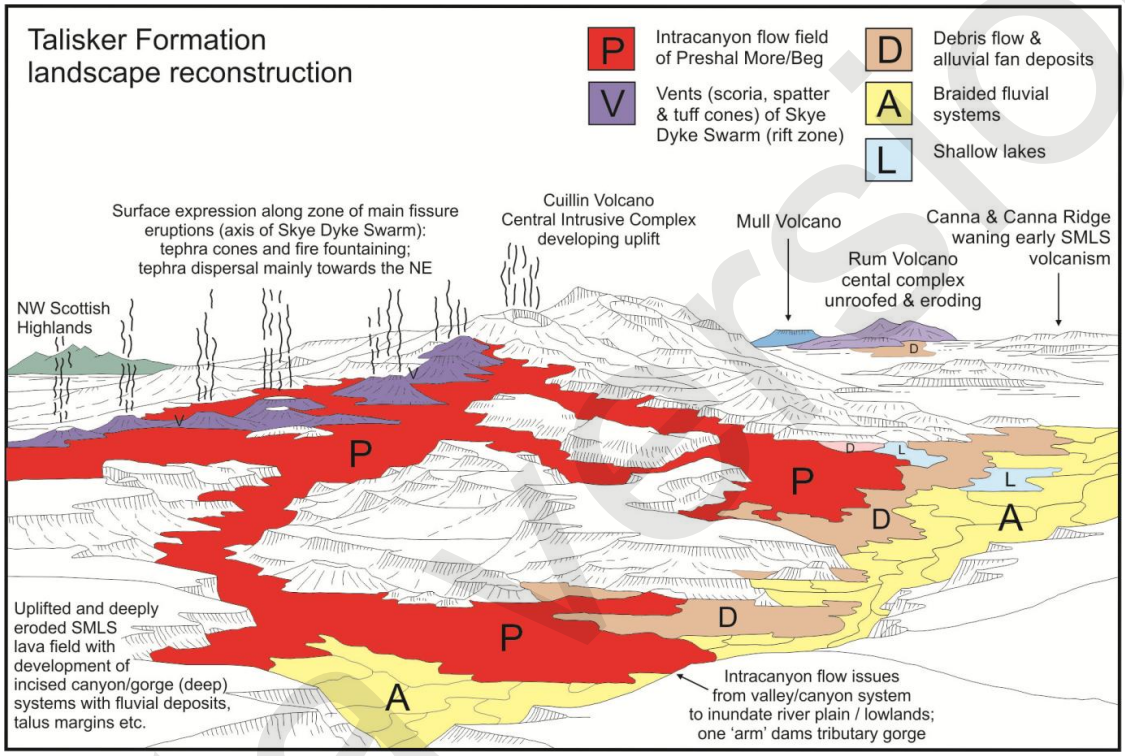


Figure 6-249: Schematic Talisker Formation intra-canyon lava landscape reconstruction (after Bell & Williamson 2013).

6.5.3 North of Loch Harport and the Cuillin

Correlations between the various subdivisions of the lava sequence on Minginish, outlined above, and the sequences north of Loch Harport and north of the Cuillin have not been established, mainly due to poor exposure. The sequence north of Loch Harport has tentatively been assigned to two members, the Harport and Meadale members, of the Roineval Formation (BGS 2000), characterised by interbedded compound basaltic lavas and sheet-like hawaiite lavas, together with laterally restricted (ponded?) plagioclase-porphyritic and near-aphyric mugearite lavas (Figure 6-250; Figure 6-251). The Roineval Formation is most likely separated from the Coire na Circe Formation (with four members: Allt Dearg (oldest), Sròn a' Ghrobain, Coire Daraich and Am Màm (youngest)), north of the Cuillin, by a major fault zone in Glen Drynoch. Similarly, the Sligachan Formation, north of Loch Sligachan, is dominated by interbedded compound basaltic lavas and sheet-like hawaiite lavas, with an older Cnoc an t-Sìthein Member and a younger Meall Odhar Member, both poorly constrained.

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Figure 6-250: Roineval Formation plagioclase macro-porphyritic basaltic lava forming the plateau of Roineval, NE of the head of Loch Harport. View towards the north from the south side of Loch Harport.



Figure 6-251: Roineval Formation plagioclase macro-porphyritic basaltic lava(s) forming the summit of Roineval, NE of the head of Loch Harport. View NE towards the summit.

Preliminary version

The Fionn Choire Formation crops out in the Fionn Choire - Meall Odhar area on the NW side of the Cuillin, accessed from the Bealach a' Mhàim, and comprises a complex sequence of fragmental deposits, both pyroclastic and volcaniclastic, together with amygdaloidal basalt, hawaiite and mugearite lavas. The compositionally evolved nature of much of the sequence has produced a distinctive landscape, significantly devoid of vegetation because of the nutrient-poor nature of these rocks (Figure 6-252). Superficially, the level of exposure looks good, but much of it comprises frost-shattered scree that is not *in situ*. Exposure tends to be slightly better where the sequence is cut by dolerite and basalt minor intrusions, for example in the Allt Mòr an Fhinn Choire (Figure 6-253), some associated with the Cuillin Intrusive Centre to the south (Chapter 9) and some members of the NW-SE -trending Syke Main Dyke Swarm (Chapter 7). The interbedded basalt, hawaiite and mugearite lavas are not well exposed and their field relationships are difficult to determine.



Figure 6-252: Distinctive vegetation-poor nature of the Allt Mòr an Fhinn Choire area in Fionn Choire, comprising silicic pyroclastic and volcaniclastic lithologies of the Fionn Choire Formation. View south towards Bruach na Frithe.

Boards version



Figure 6-253: Minor basaltic intrusions within silicic volcanic lithologies in the Allt Mòr an Fhinn Choire, Fionn Choire. View towards the west.

A variety of clastic lithologies are recognised, all hydrothermally altered with abundant secondary hydrous minerals such as epidote and chlorite, due to their proximity to the Cuillin Intrusive Centre (to the south) (Chapter 9), including stratified lithic lapilli-tuffs (Figure 6-254), crystal-rich lapilli-tuffs (Figure 6-255), and relatively coarse unstratified (matrix-supported and clast-supported) breccias (Figure 6-256). Clasts within these deposits are of a variety of Paleocene lithologies, including basalt, hawaiite, mugearite and granite, together with sandstone, which may have been derived from the Late Proterozoic Torridonian Supergroup (Chapter 2). The dominant crystals within the crystal-rich lapilli-tuffs are plagioclases, ranging between euhedral forms and angular fragments, some well over 1 cm long. Matrix material to the lapilli-tuffs is very fine-grained and very altered, comprising original ash, together with silt and sand grade granular material. Also present and potentially constituting a large part of the Fionn Choire Formation, are pale-weathering, distinctly banded units, commonly with abundant folds, that have been variously interpreted as rhyolite lavas (Harker 1904), trachyte lavas (Thompson 1967), and rhyolitic ignimbrites and trachytic-rhyolitic lava-like ignimbrites (Drake 2014) (Figure 6-257).

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Figure 6-254: A stratified sequence of relatively crystal-rich lapilli-tuff, laminated lapilli-tuff (with local cross stratification) and more massive lapilli-tuff, Fionn Choire Formation, NW of Meall Odhar in the NE part of Fionn Choire. Pole *ca*. 1 m long.

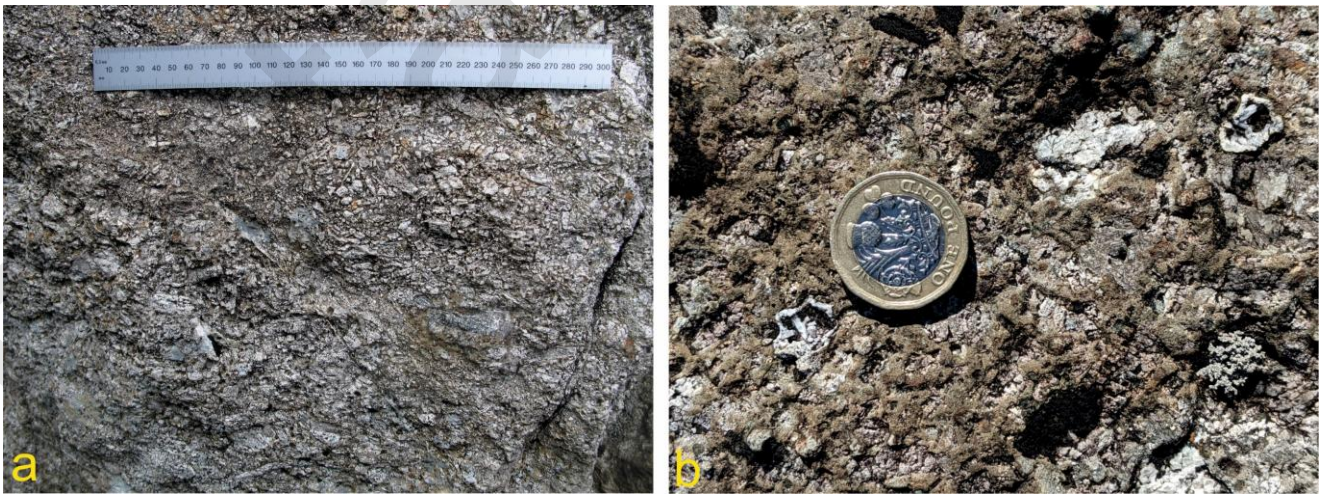


Figure 6-255: (a) Crystal-rich tuff with pale plagioclase crystals in the Fionn Choire Formation, Fionn Choire, ruler 30 cm long; and, (b) detail of crystal-rich tuff in the Fionn Choire Formation, Fionn Choire, coin *ca*. 24 mm across.

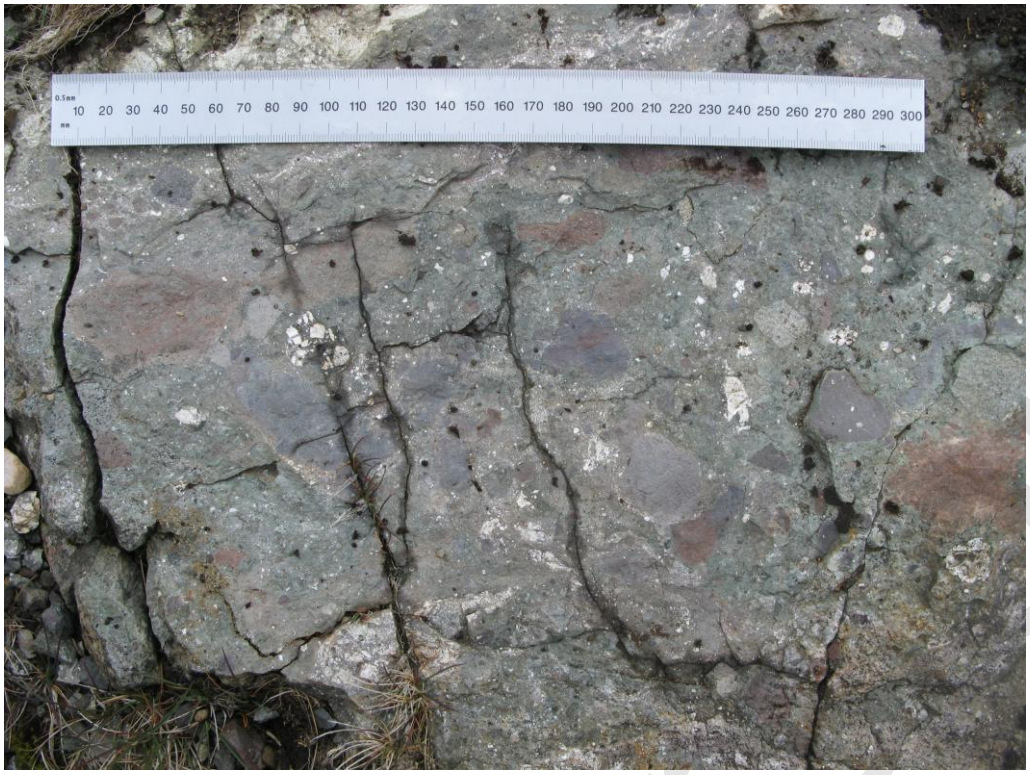


Figure 6-256: Unstratified, polylithic breccia, with conspicuous angular to sub-angular fragments of lava lithologies, of the Fionn Choire Formation, Fionn Choire. Ruler 30 cm long.



Figure 6-257: Trachytic lava-like ignimbrite of the Fionn Choire Formation, with minor folds within its well-developed fabric. Ruler 30 cm long.

6.5.4 Central Skye

Other relatively minor disparate outcrops of the Skye Lava Field occur within central Skye: on Strathaird, outliers form the summits of Ben Cleat and Ben Meabost, and from Ben Leacach north to Slat Bheinn, An Càrnach and An Stac; on Belig, NW of the head of Loch Slapin; on the south side of Sgùrr na Stri; at Creagan Dubh in Strath; on the SW side of Creag Strollamus, west of Broadford; north of the summit of Beinn na Crò in Strath; east of the Allt Stapaig in south Scalpay; and, on the summit ridge of Glamaig in the Western Red Hills.

Only the sequence on Strathaird has been examined in detail (Almond 1960, 1964). Here, a *ca*. 300 m thick sequence of lavas crops out over an area of *ca*. 18 km^2, overlying Jurassic and Cretaceous sedimentary rocks with a small amount of angular discordance (Chapter 3). Both the Mesozoic strata and the Paleocene volcanic rocks have been flexed during the emplacement of the Cuillin Intrusive Complex, most obviously on An Stac, east of Blà-bheinn (Figure 6-258). Almond (1964) identified four units, as set out in Figure 6-259.



Figure 6-258: Inclined basaltic lavas overlying poorly exposed Mesozoic strata forming An Stac. In the background, the lower slope of Blà-bheinn is composed of younger gabbros of the Cuillin Intrusive Centre. View towards the west from the head of Loch Slapin.

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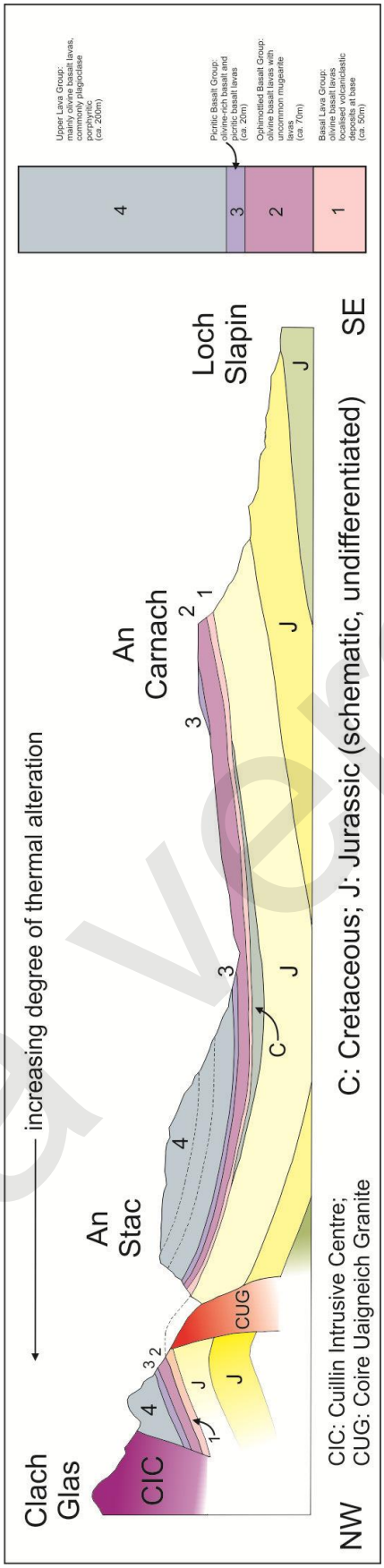


Figure 6-259: Lava stratigraphy on Strathaird (after Almond 1964).

At the base of the sequence, at the northern end of the east-facing ridge of An Càrnach, Almond (1960) briefly describes fragmental rocks that are interpreted as being of pyroclastic origin, although possibly

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having undergone some form of sedimentary reworking. These rocks have subsequently been interpreted as silicic pyroclastic rocks (Drake & Beard 2012), and subsequently (re)interpreted by the same authors (Drake *et al*. 2017) as being an ejecta layer associated with some sort of meteorite impact that pre-dated the eruption of the lava field.

The close proximity of the lavas on Strathaird (Figure 6-259), south of Sgùrr na Stri (Figure 6-260) and south of Gars-bheinn on the north of Soay Sound (Figure 6-261) has led to changes in their characteristics: the replacement of brown weathered surfaces and red palaeosols by grey surfaces and reddish-brown palaeosols, respectively, and joints (including columnar joints) being sealed with hydrothermal minerals such as epidote, chlorite, various zeolites and carbonates. Secondary minerals have replaced primary (magmatic) minerals. Almond (1964) identified three zones of alteration/metamorphism within this thermal aureole of the intrusive complex and the development of new, non-magmatic features, as detailed in Chapter 9.

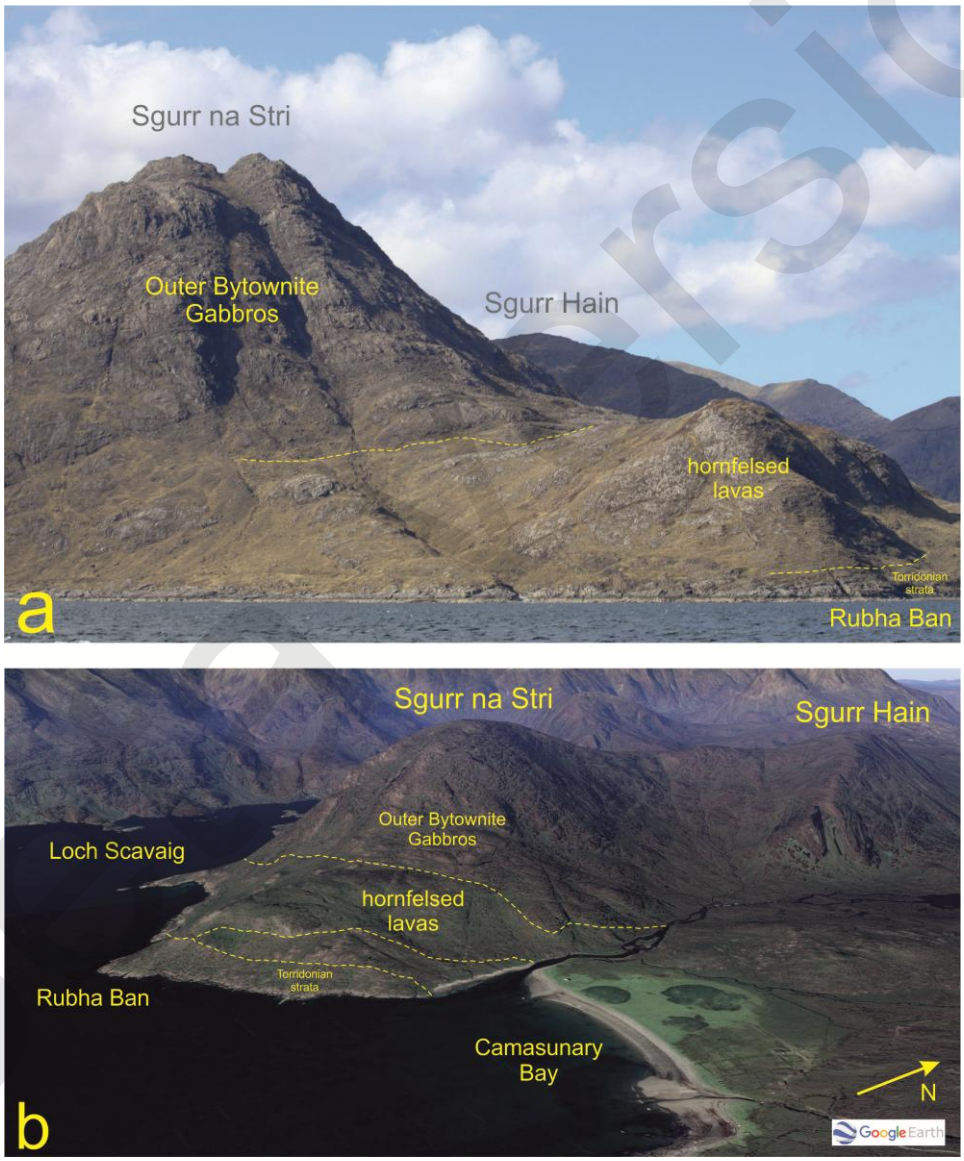


Figure 6-260: (a) Hornfelsed basaltic lavas unconformably overlying Torridonian Supergroup strata, forming the low-lying southern part of the Sgùrr na Stri peninsula, view towards the north; and, (b) annotated oblique Google Earth© image of the Sgùrr na Stri peninsula.

Borehole version



Figure 6-261: Hornfelsed basaltic lavas unconformably overlying Torridonian Supergroup strata, south of Garsbheinn, south Cuillin. The high, scree-covered ground is part of the Paleocene Cuillin Intrusive Centre. View towards the north, across Soay Sound from Soay.

Similar hydrothermally altered lavas crop out NW of the head of Loch Slapin on Belig, dipping at 30-40° towards the west, with obvious step or trap topography preserved (Figure 6-262). Where adjacent to the younger intrusions of the Cuillin Intrusive Centre and the granite that crops out south of Belig (Chapter 9), the rocks are intensely altered and recrystallized.



Figure 6-262: Trap or step topography of basaltic lavas on Belig, NW of the head of Loch Slapin, dipping towards the west. View towards the NW.

At Creagan Dubh in Strath, basaltic lavas unconformably overlie rocks of the Lewisian Gneiss Complex (Figure 6-263; Figure 6-264; Figure 6-265). The unconformity has some topographic relief. Like the lavas adjacent to the Cuillin Intrusive Centre on Strathaird and on Belig, they are intensely hydrothermally altered and the stratified character of the sequence is less obvious that in the main sequences in north and west-central Skye. Towards the top of the preserved sequence are laterally discontinuous cobble and pebble conglomerates and volcaniclastic deposits. Of similar character, north of the summit of Beinn na Crò in the Eastern Red Hills, are poorly exposed hydrothermally altered, hornfelsed lavas, intruded by gabbros and granites.

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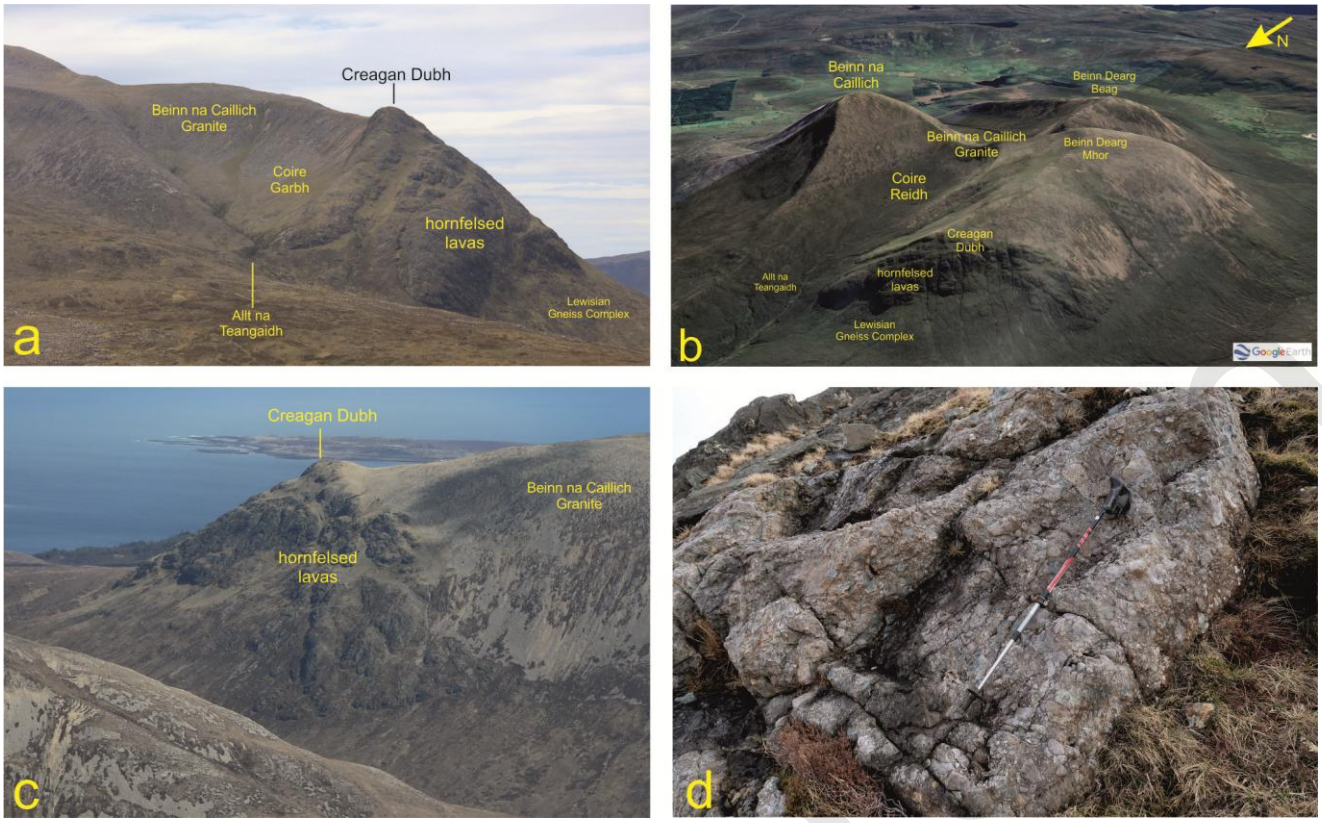


Figure 6-263: (a) Hornfelsed basaltic lavas of Cregan Dubh overlying the (basement) Lewisian Gneiss Complex, view towards the south from Creag Strollamus; (b) annotated oblique Google Earth© image of the area centred on Creagan Dubh, view towards the SE; (c) Creagan Dubh from the east side of Blà-bheinn, view towards the NE; and, (d) detail of conglomerate interbedded with lavas on Creagan Dubh, pole *ca*. 1 m long.



Figure 6-264: Dark basaltic lava sequence of Creagan Dubh, intruded by pale granites of the Eastern Red Hills Intrusive Centre (top right). View towards NE from Srath Beag.

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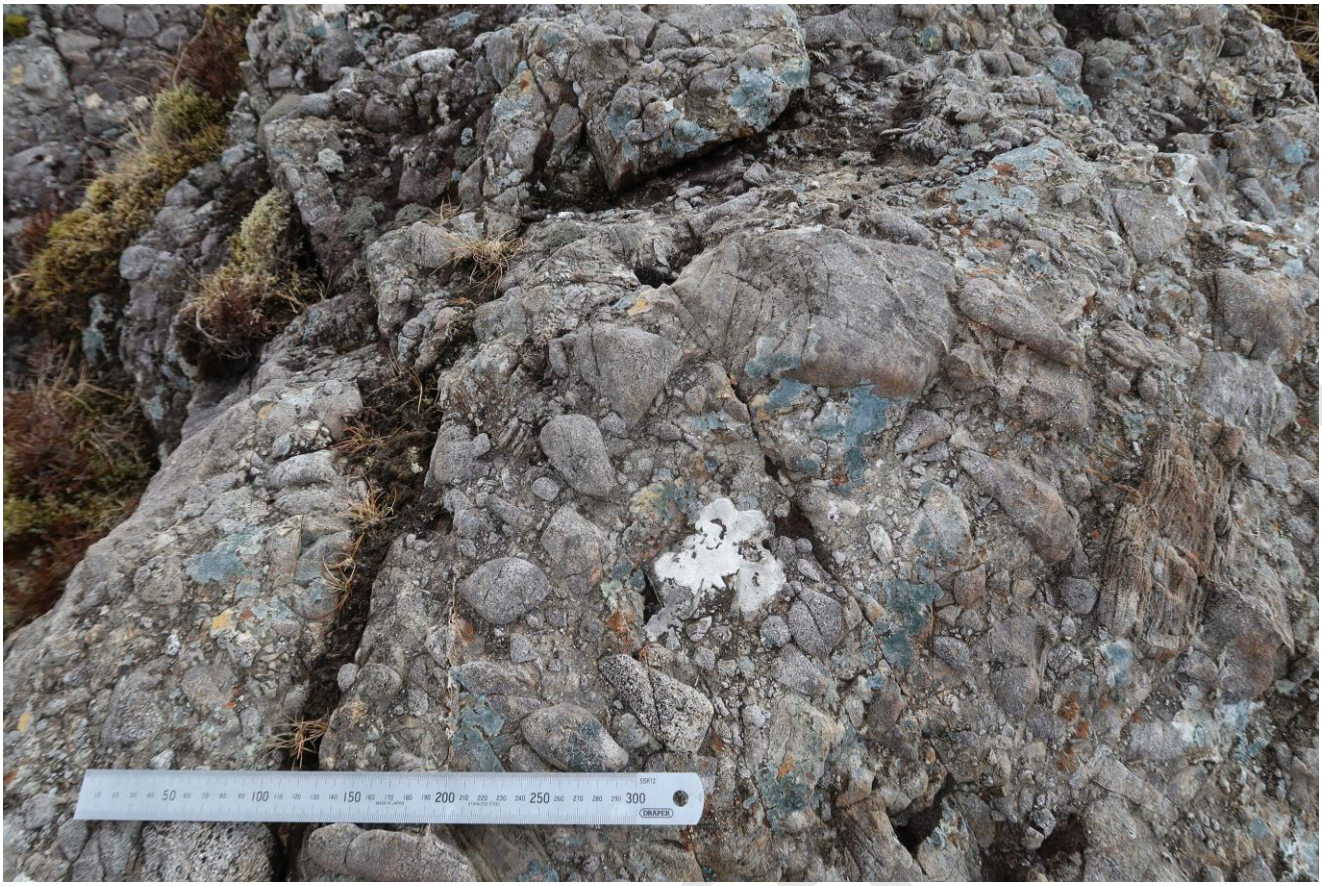


Figure 6-265: Matrix-supported pebble and cobble breccia/conglomerate interbedded with amygdaloidal basaltic lavas, Creagan Dubh, with abundant clasts of orange-weathering Torridonian sandstone. Ruler 30 cm long.

The lavas preserved in the vicinity of Creag Strollamus, west of Broadford, are hydrothermally altered and lie unconformably upon either Torridonian strata or Cambro-Ordovician dolostones. Amygdaloidal texture is relatively common, but the overall structure and orientation of the lavas are not clear. Interbedded pebble and cobble breccias and conglomerates crop out north of Loch Cùil na Creige, west of Creag Strollamus (Figure 6-266).

The lavas on the south side of Scalpay, directly across Caolas Scalpay from Creag Strollamus, overlie Mesozoic strata and their stratified character is more obvious, with identifiable units dipping towards the SE (Figure 6-267).

Beta version



Figure 6-266: Matrix-supported pebble and cobble breccia/conglomerate interbedded with amygdaloidal basaltic lavas north of Loch Cùil na Creige, west of Creag Strollamus, with abundant clasts of orange-weathering Torridonian sandstone and white Cambrian quartzite (sandstone). Pole *ca*. 1 m long.



Figure 6-267: Trap topography of inclined (towards the SE) basaltic lavas on the east side of the Allt Stapaig on Scalpay. View towards the NE from west of Creag Strollamus on Skye.

Much of the twin summits of Glamaig - Sgùrr Mhairi and An Coileach - south of Loch Sligachan in the Western Red Hills, are composed of similarly altered lavas, below which are younger granites of the Western Red Hills Intrusive Centre that are responsible for their general lack of primary features, as seen north of Loch Sligachan and over much of the ground to the north (Figure 6-268; Figure 6-269).

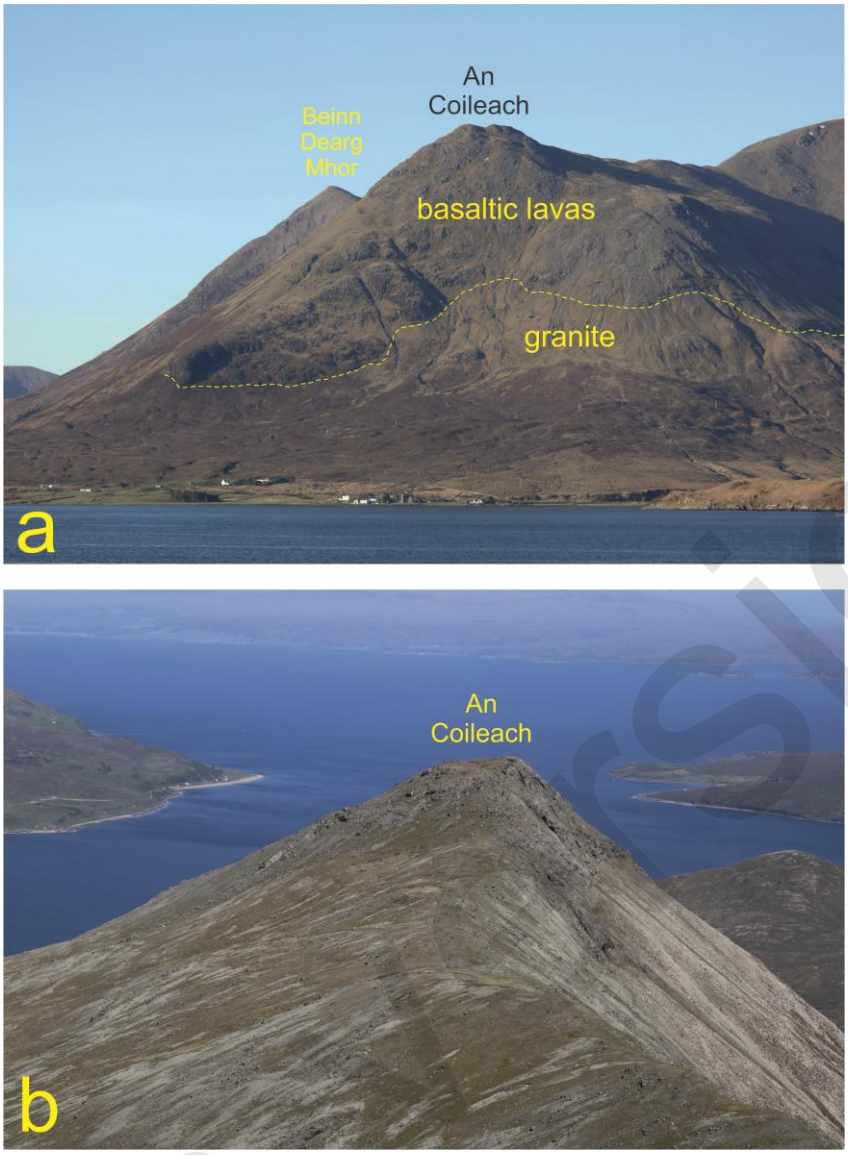


Figure 6-268: Hornfelsed basaltic lavas forming an inclined cap to younger pale-weathering granites of the Western Red Hills Intrusive Centre on: (a) the An Coileach ridge of Glamaig, view towards SW from Raasay House, Raasay; and, (b) from the summit of Sgùrr Mhairi (Glamaig), NE towards An Coileach.



Figure 6-269: Hornfelsed basaltic lavas forming an inclined cap to younger pale-weathering granites of the Western Red Hills Intrusive Centre on: the An Coileach ridge of Glamaig, view towards the west.

Beta version

6.5.5 Raasay

On Raasay, a small outlier of the Skye Lava Field forms the conspicuous summit of Dùn Caan (Figure 6-270; Figure 6-271), consisting of at least two distinct lavas, the upper of which, forming the top crag, is distinctly (flow) banded. Below these lavas, most easily identified from loose scattered fragments on the path leading to the summit, is an interval of distinctly green glauconitic sandstone, the Cenomanian (Upper Cretaceous) Morvern Greensand Formation (Chapter 3).



Figure 6-270: Basaltic lavas forming the summit of Dùn Caan on Raasay. View towards the east across Loch na Meilich.



Figure 6-271: Detail of (flow) banding in basaltic lava forming the summit of Dùn Caan on Raasay. Hammer *ca.* 30 cm long.

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6.5.6 Canna and Sanday

The southern extension of the Skye Lava Field occurs on the tidally joined (now by a bridge) islands of Canna and Sanday (Figure 6-272; Figure 6-273; Figure 6-274; Figure 6-275; Figure 6-276; Figure 6-277), as well as on the island of Rum (see below).



Figure 6-272: Inclined Google Earth© image of Canna and Sanday (near right), viewed towards the north.



Figure 6-273: Canna and Sanday (near centre) viewed towards north from Rum.



Figure 6-274: East Canna, with the sea cliffs of Compass Hill, viewed towards the north from Rum.

Beta version



Figure 6-275: Paleocene lavas on Bloodstone Hill, NW Rum, with Canna and Sanday in the distance.

One substantial reason for linking the Canna, Sanday and Rum lavas with the main outcrops on Skye is the presence of distinctive clasts within interbedded conglomerates in all these outcrops. Their presence can be explained by the unroofing of the older Rum Central Complex, upon which the Rum lavas unconformably overlie, and their transport north by a fluvial drainage system during periods of volcanic quiescence.

The near-to-horizontal sequence on Canna and Sanday is at least 200 m thick (Emeleus 1997), with the oldest part in SE Sanday (Figure 6-277) and the youngest part in east and west Canna. Figure 6-278 is a generalized vertical section.



Figure 6-276: The Compass Hill crags of east Canna, composed of basaltic lavas and coarse breccias, conglomerates and sandstones. Height of cliffs *ca.* 120 m. View from Rum towards the NW.

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Figure 6-277: The south coast of Sanday, with the sea stacks, Dùn Beag (centre) and Dùn Mòr (left), and Compass Hill, east Canna in the distance.

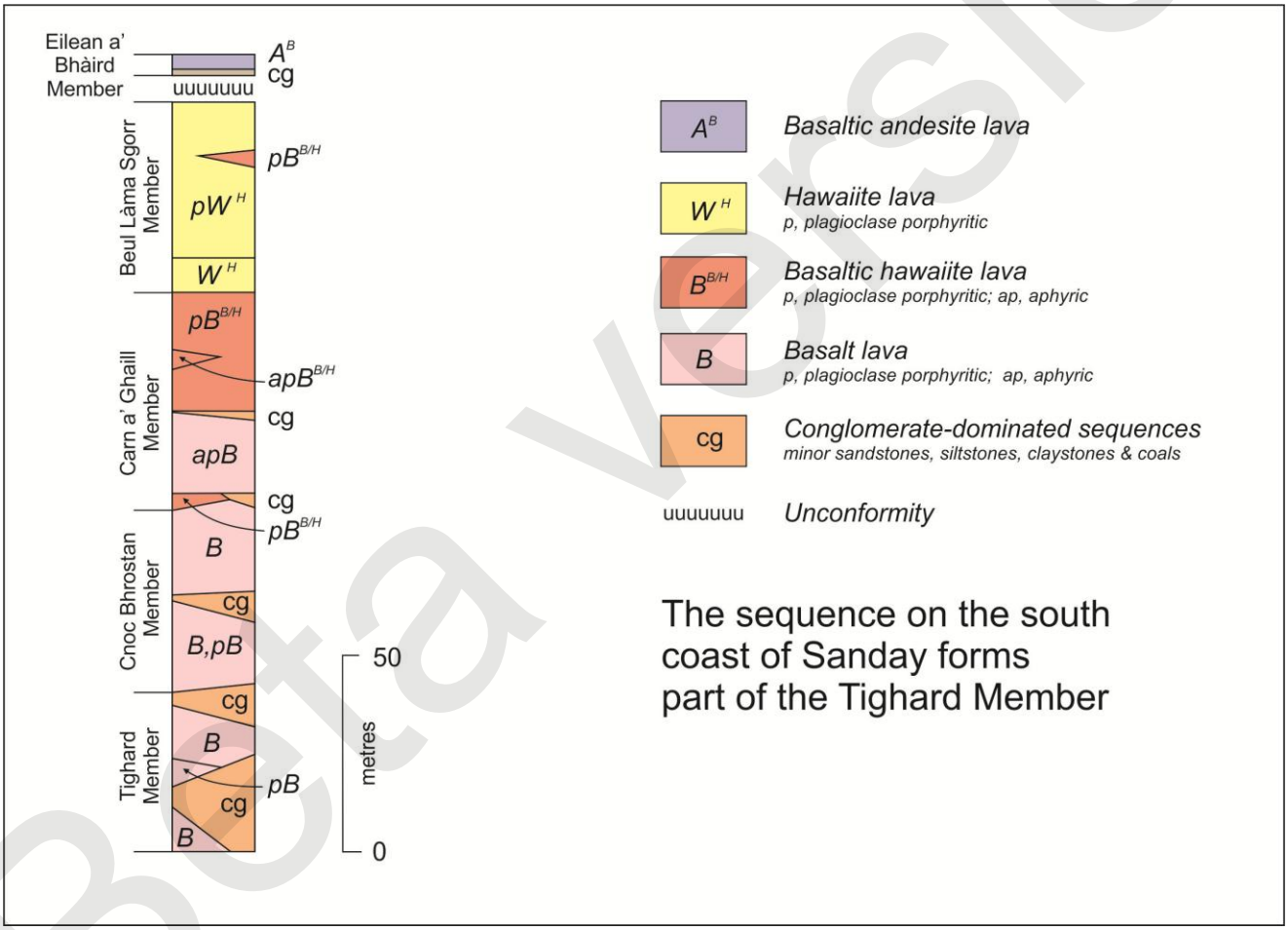


Figure 6-278: Volcanic stratigraphy of the Canna Lava Formation on Canna and Sanday (after Emeleus 1997).

Basaltic types dominate, with or without phenocrysts of plagioclase. Hawaiite lavas with plagioclase phenocrysts up to 3 cm cap the preserved sequence at Carn a' Ghaill and Beul Làma Sgorr in central-north Canna (Figure 6-278; Figure 6-279; Figure 6-280; Figure 6-281; Figure 6-282; Figure 6-283;

Figure 6-284; Figure 6-285). Columnar- and prismatic-joined simple lavas are common, as are reddened tops to both simple and compound types. NW-SE -trending faults complicate the overall sequence, making island-wide correlations difficult.

Beta version



Figure 6-279: Compass Hill cliff, east Canna.



Figure 6-280: Volcanic sequence at the top of the Compass Hill section, capped by a distinctly columnar-jointed basaltic lava.

Preliminary version

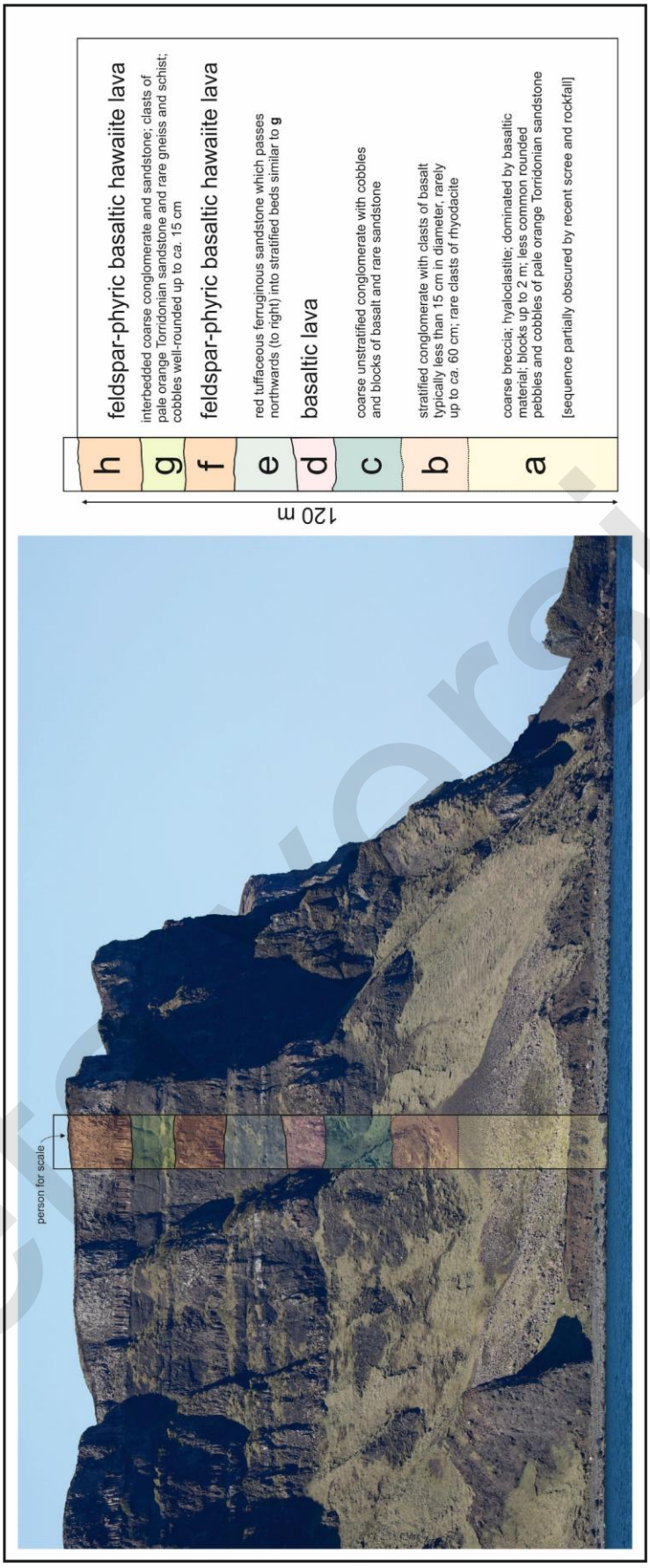


Figure 6-281: Lithology log for the cliff section, Compass Hill, east Canna.

Beta version



Figure 6-282: Detail of the upper portion of the Compass Hill sequence, comprising columnar-jointed feldspar-phyric basaltic hawaiite lavas (units f & h), interbedded with conglomerates and sandstones.



Figure 6-283: Poorly stratified boulder breccia, base of sequence at Compass Hill, east Canna.



Figure 6-284: Columnar-jointed basaltic lavas, Am Beannan section, SW Canna.



Figure 6-285: Columnar-jointed basaltic lavas, Am Beannan – Iola-Sgorr section, SW Canna.

The Tighard and Cnoc Bhrostan members comprise simple and compound basaltic lavas interbedded with a wide variety of clastic sedimentary units and crop out over much of Sanday and in east Canna at Compass Hill. Many of the lavas are up to 20 m thick and columnar- and prismatic-jointed varieties are common. The sedimentary units thin towards the west on Canna.

The volcanic-sedimentary relationships are complex and may possibly be the most informative in terms of depositional processes within the HIP. First recognised by Geikie (1896, 1897) and described in detail by Harker (1908), they comprise boulder beds, conglomerates, sandstones, siltstones, mudstones and thin coals and are commonest in the lowest part of the sequence along the south coast of Sanday, especially in the rock pillars of Dùn Mùr and Dùn Beag, at Cnoc Ghreannabric, and at Tallabric, and in the cliffs of Compass Hill (at least 50 m thick) at the east end of Canna. Williamson & Bell (2027) provide a detailed description and interpretation of the sequences on the south coast of Sanday. (Figure 6-286; Figure 6-287; Figure 6-288; Figure 6-289; Figure 6-290; Figure 6-291; Figure 6-292).

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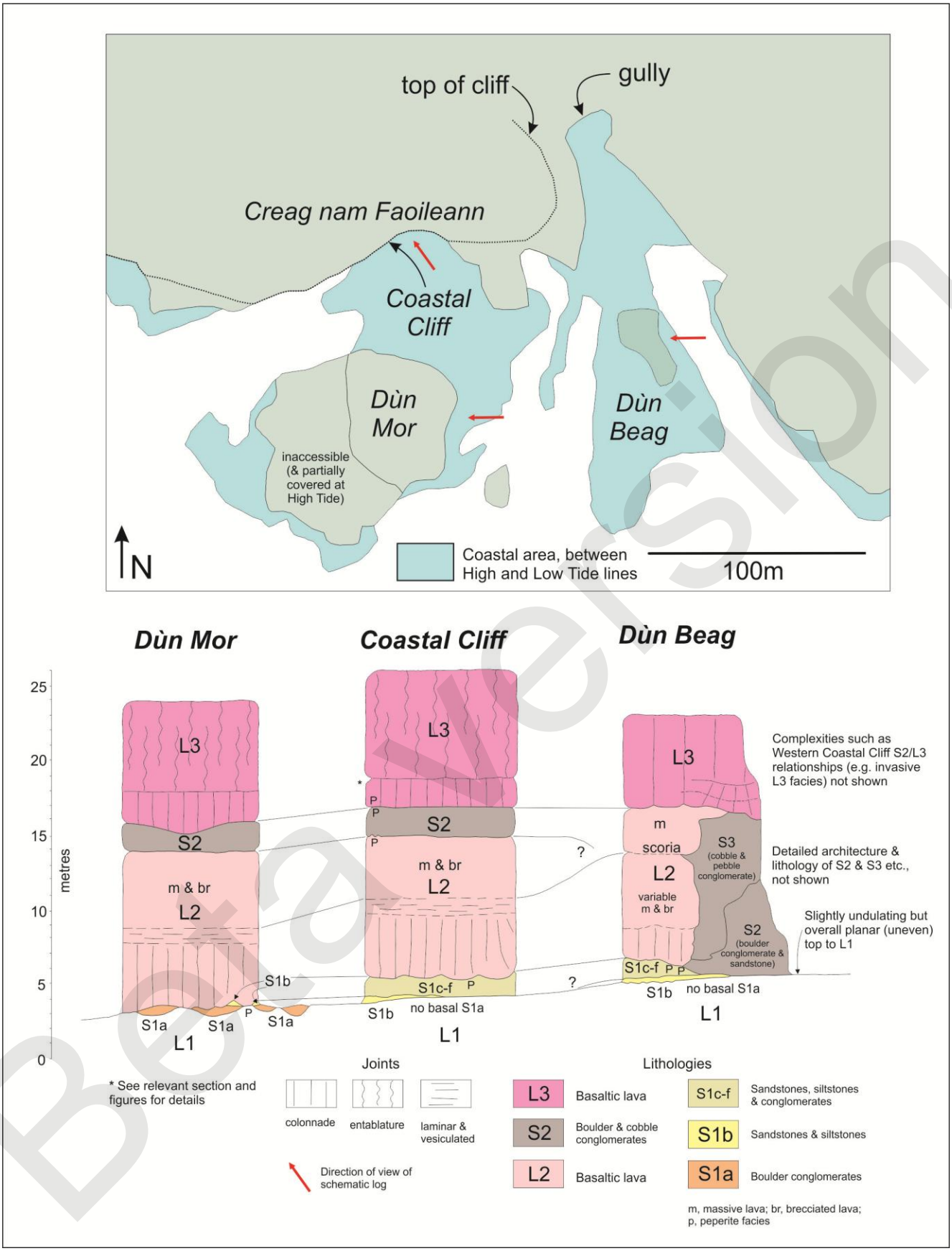


Figure 6-286: Location map and schematic section for Dùn Mòr, the Coastal Cliff and Dùn Beag in the Creag nam Faoileann Section, Sanday.

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Figure 6-287: The Dùn Mòr and Dùn Beag sea stacks, south coast of Sanday. Viewed towards the west.

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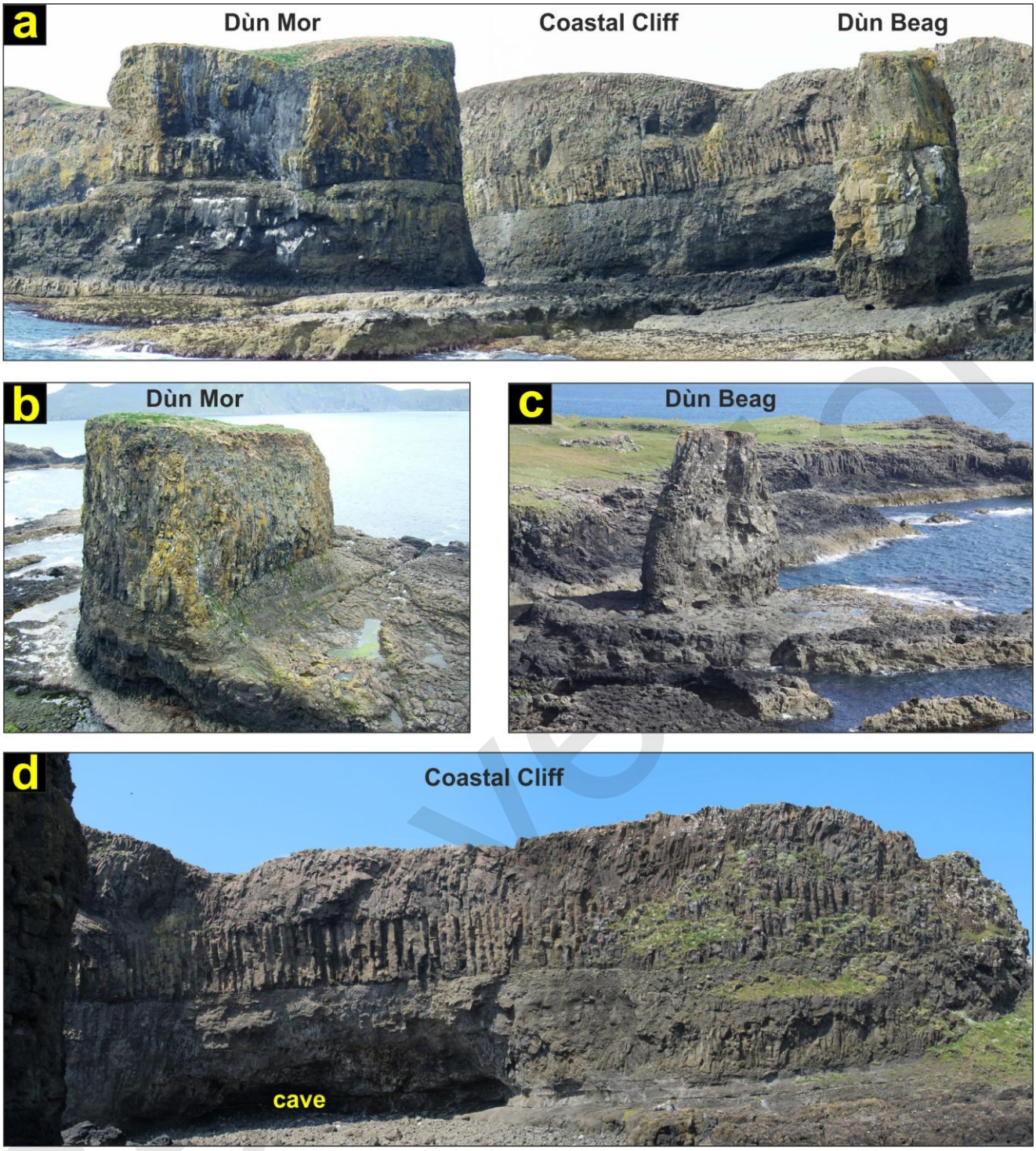


Figure 6-288: Field views of Dùn Mòr, the Coastal Cliff and Dùn Beag in the Creag nam Faoileann Section.

Be

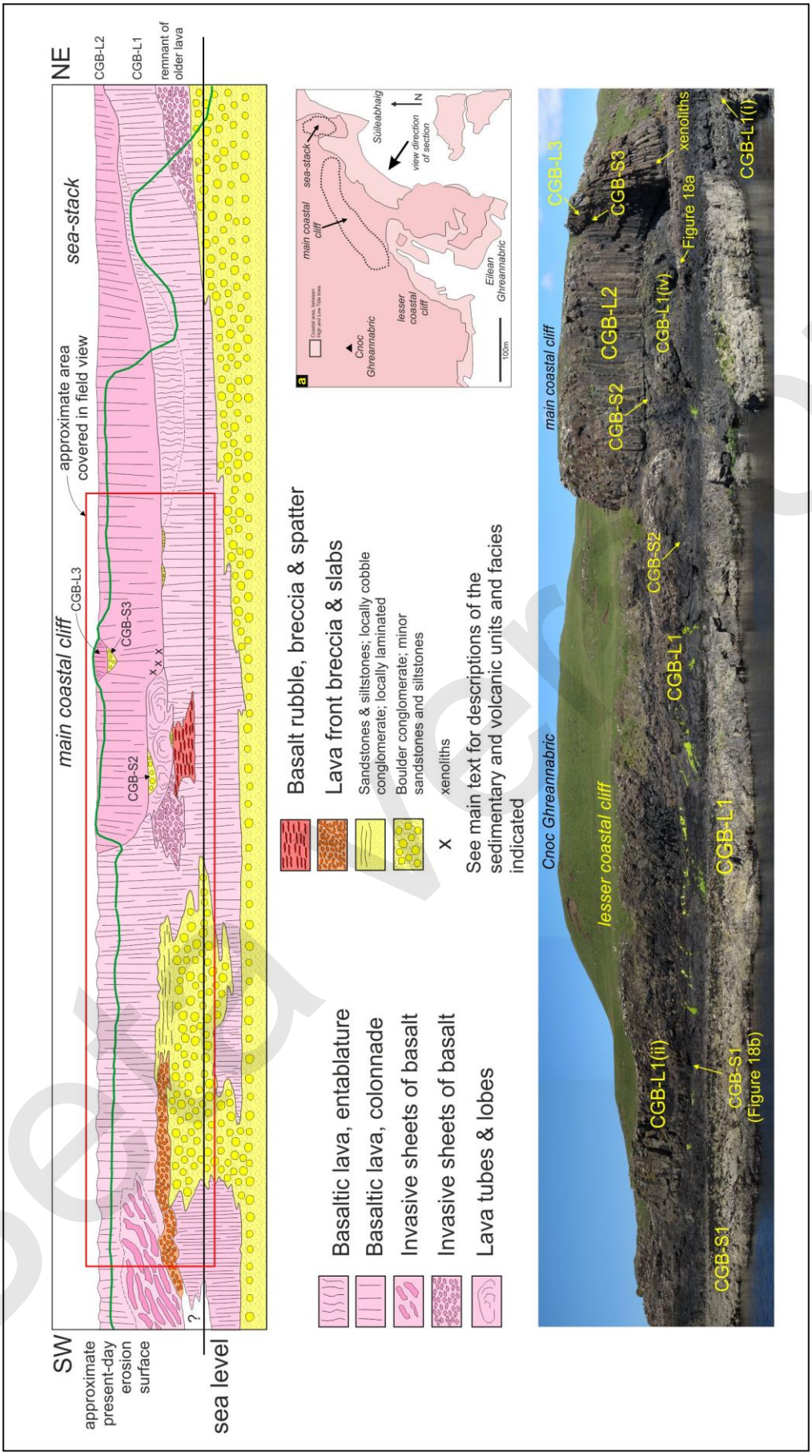


Figure 6-289: Schematic cross-section and field view panorama of the Cnoc Ghreannabric (CGB) section.

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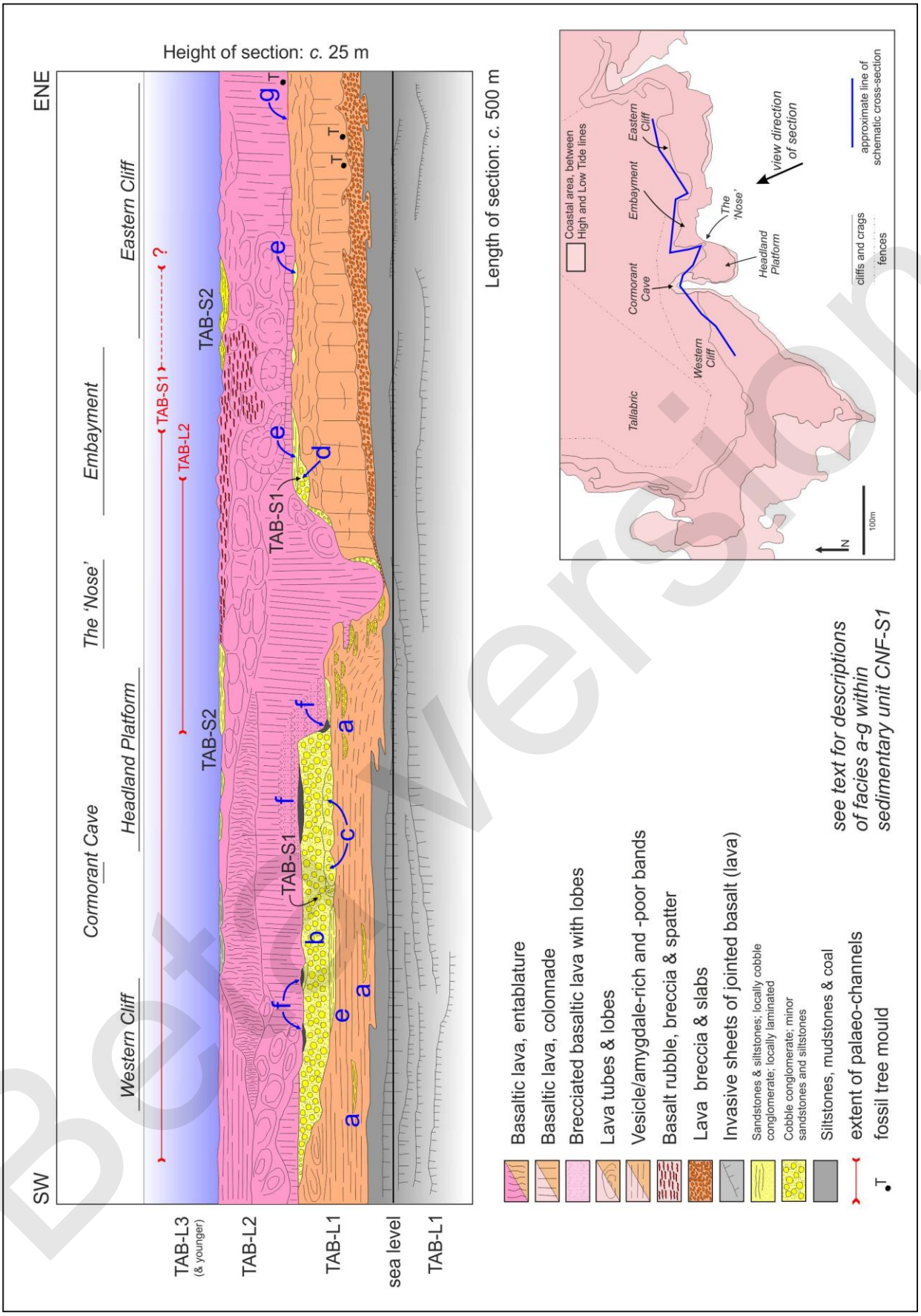


Figure 6-290: Schematic cross-section and location map of the Tallabric (TAB) section.

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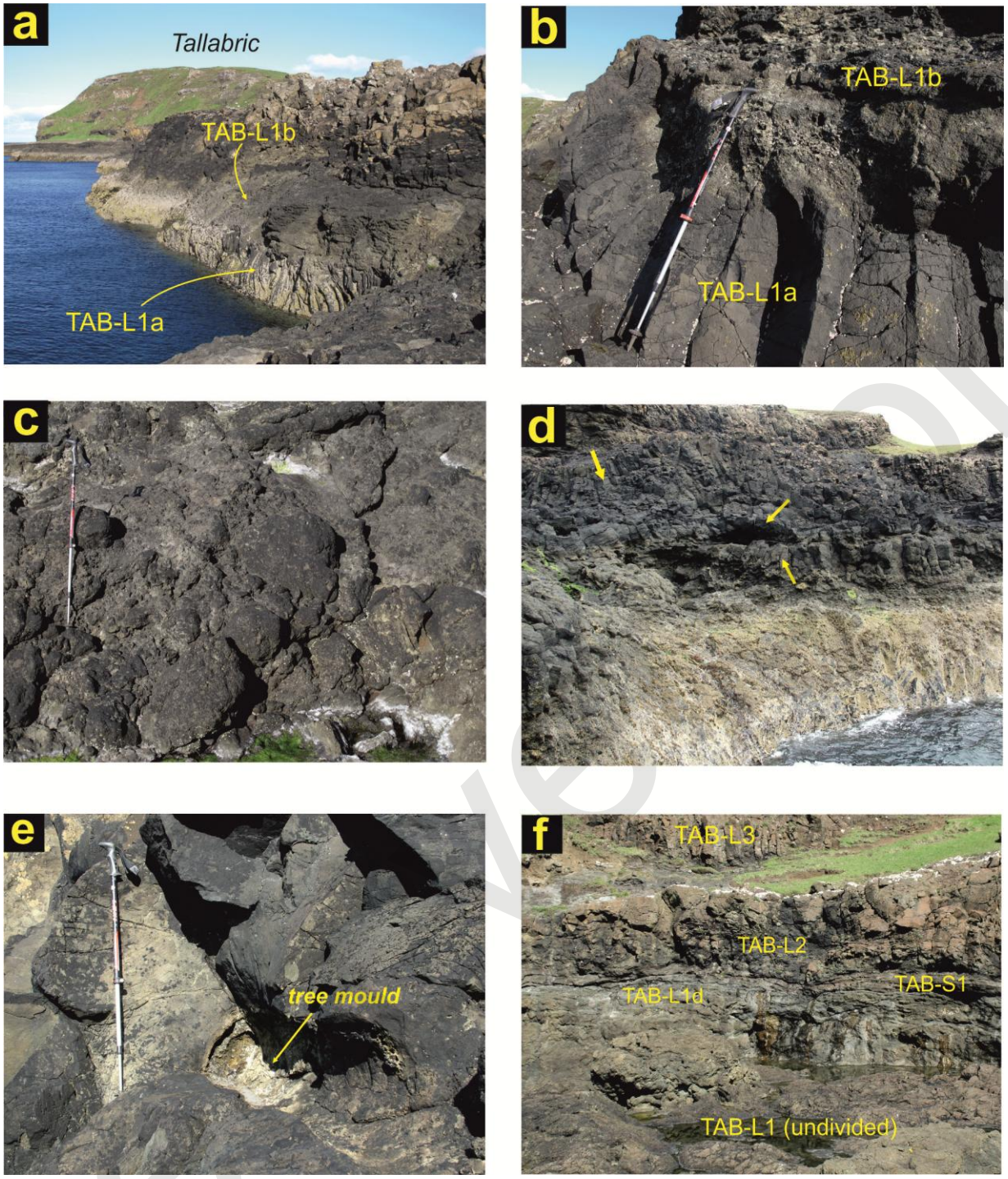
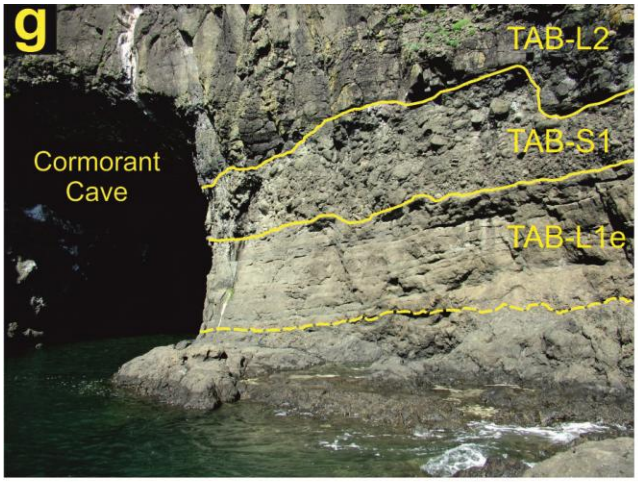
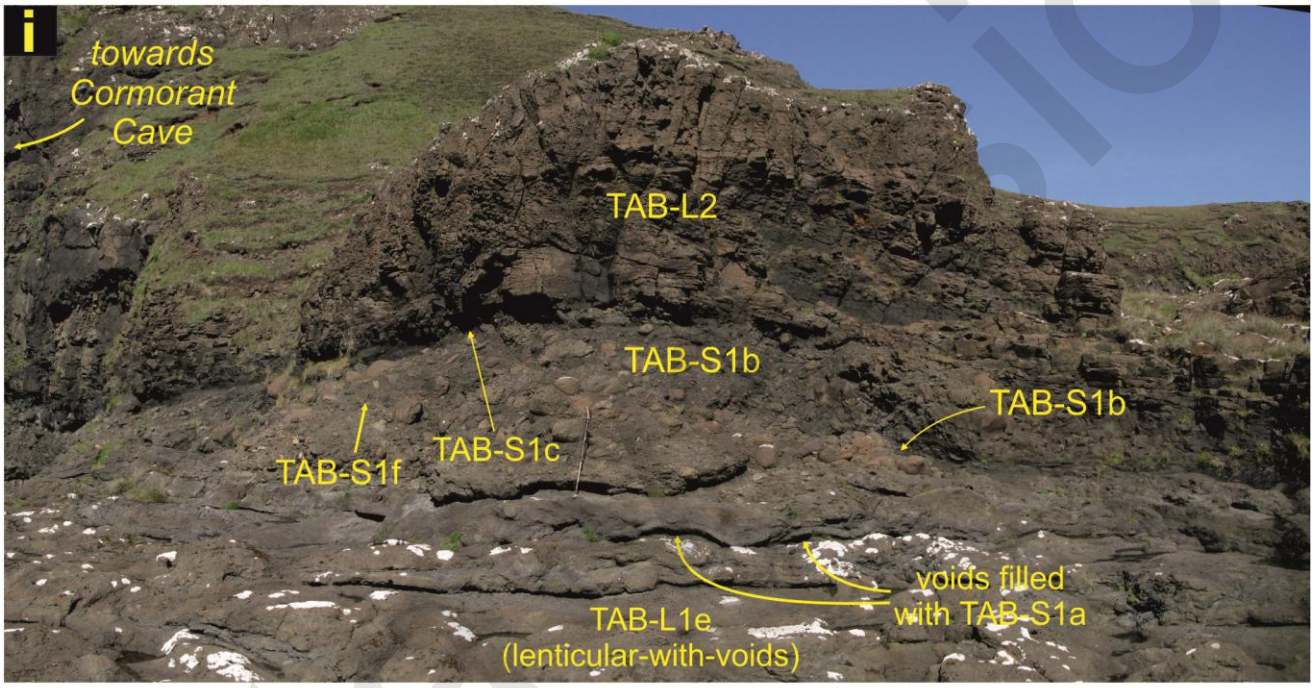


Figure 6-291: Field views of various features within the volcanic and sedimentary units of the Tallabric (TAB) section. (a) View looking west along the Tallabric section showing the coastal exposures of TAB-L1; (b) Joint patterns within TAB-L1a and overlying breccia TAB-L1b towards the eastern end of the section, pole *ca.* 1 m long; (c) Vesicular basalt-clast breccia of TAB-L1b towards the eastern end of the Tallabric section, pole *ca.*1 m long; (d) Sheets of TAB-L1c with poorly-developed prismatic joints and void cores (arrowed); (e) Tree mould within TAB-L1c towards the eastern end of the section, pole *ca.* 1 m long; (f) TAB-L1d at the base of the Eastern Cliff.

Preview


g
TAB-L2
TAB-S1
Cormorant
Cave
TAB-L1e


h


i
towards
Cormorant
Cave
TAB-L2
TAB-S1b
TAB-S1b
TAB-S1f
TAB-S1c
voids filled
with TAB-S1a
TAB-L1e
(lenticular-with-voids)


j


k

[OVER]

Figure 6.291: Field views of various features within the volcanic and sedimentary units of the Tallabric (TAB) section. (g) TAB-L1e, TAB-S1 conglomerate and TAB-L2 on the east side of Cormorant Cave; (h) Compact tabular 'inflation' sheets of TAB-L1e on the east side of Cormorant Cave, ruler 30 cm long; (i) TAB-L1e (lenticular-with-voids), TAB-S1b, TAB-S1c and TAB-L2 at the back of the Headland Platform between Cormorant Cave and The Nose, pole *ca.* 1 m long; (j) Disrupted sheets of basalt of TAB-L1e on the Headland Platform, pole *ca.* 1 m long; (k) 'Lava rise' structure composed of disrupted sheets of basalt of TAB-L1e on the Headland Platform, pole *ca.* 1 m long.

Plant fragments are poorly preserved within some of the siltstones, especially at Tallabric on Sanday and at the east end of Camas Thairbearnais in north Canna (Figure 6-292).

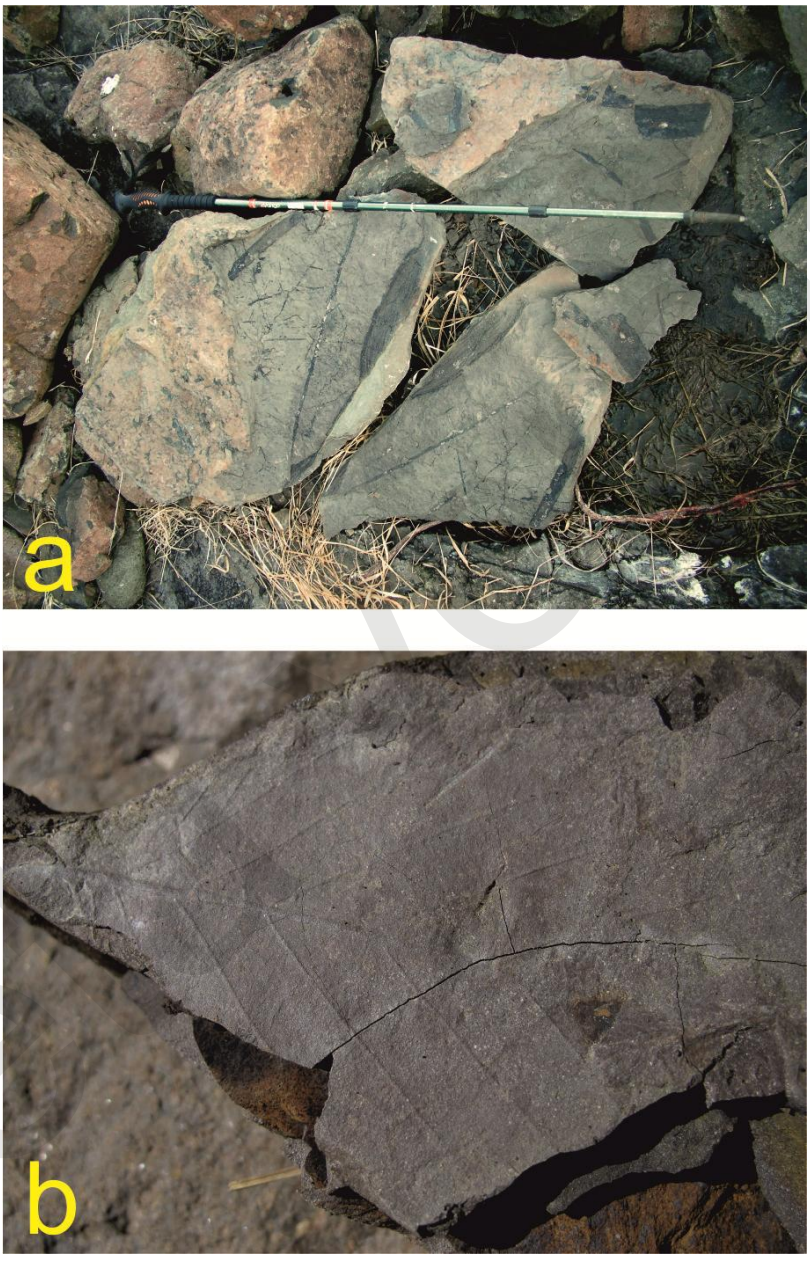


Figure 6-292: Fossil leaves and twigs within siltstone, Tallabric, SW Sanday. Pole *ca.* 1 m long.

The clast lithologies inform about their provenance. Many are simply of locally lava composition. However, clasts of feldspathic sandstone within the south Sanday and Compass Hill conglomerates and breccias are similar to Torridon Group lithologies on Rum (Chapter 2) and clasts of gneiss (Lewisian Gneiss Complex, Chapter 2) and schist (Moine Supergroup, Chapter 2) are also recognised within the uppermost conglomerates of the Compass Hill sequence (Figure 6-293; Figure 6-294).



Figure 6-293: Canyon-fill, boulder conglomerate with a vertical contact against basaltic lavas, Dùn Beag, SE Sanday. Most of the clasts are of locally derived volcanic lithilogies; however, the orange boulders and cobbles are most likely to have been derived from the basement Late Proterozoic Torridon Group sequence, NW Rum, exposed to erosion in the Paleocene. Pole *ca.* 1 m long.



Figure 6-294: Canyon-fill, boulder conglomerate, NE Canna. Most of the clasts are of locally derived volcanic lithilogies; however, the orange boulders and cobbles are most likely to have been derived from the basement Late Proterozoic Torridon Group sequence, NW Rum, exposed to erosion in the Paleocene. Lens cap *ca.* 8 cm across.

Noteworthy are clasts of granophyre within the Sanday conglomerates and clasts of porphyritic rhyodacite in the Compass Hill sequence: both types match Paleocene units of the Rum Central Complex

and provide compelling information concerning the relative ages of the Skye Lava Field and the (older) Rum Central Complex. Clasts of Mesozoic strata lithologies are conspicuously absent.

Interaction between the lavas and the sedimentary units when they were unlithified was common, producing peperites with a variety of forms (Figure 6-295; Figure 6-296).

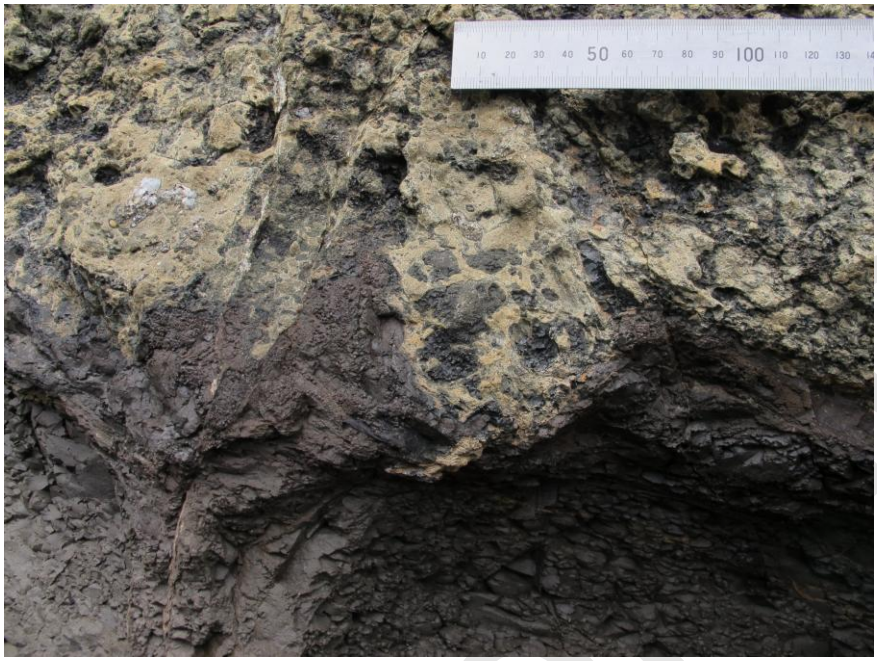


Figure 6-295: Peperite, with dark mudstone and carbonate-altered basaltic lava, base of Dùn Beag, Sanday.

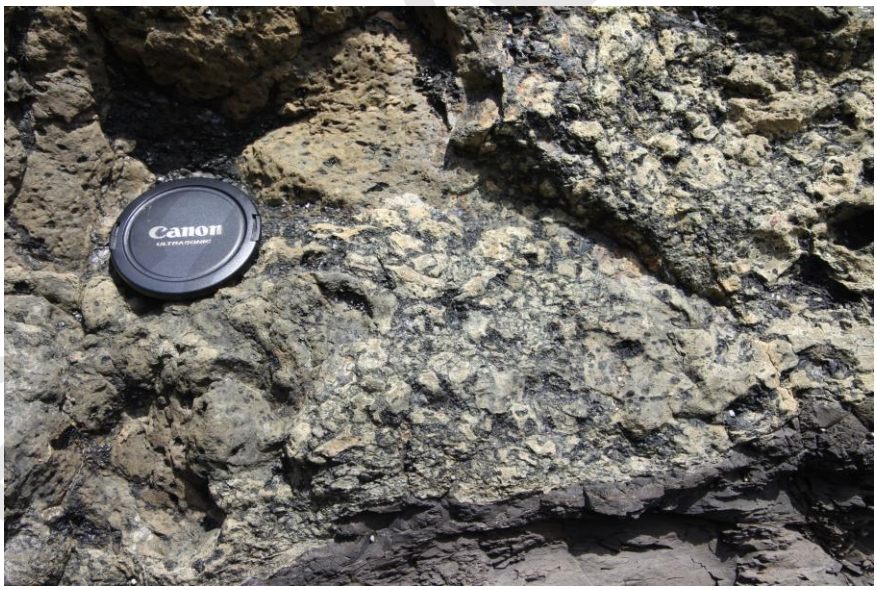


Figure 6-296: Peperite, with dark mudstone and carbonate-altered basaltic lava, base of Dùn Beag, Sanday. Lens cap *ca*. 8 cm across.

Pillow lava and hyaloclastite beds are uncommon, with one good example at Cùil a' Bhainne, west of the isthmus joining Canna and Sanday (Figure 6-297; Figure 6-298; Figure 6-299).



Figure 6-297: Dark hyaloclastite and basaltic pillows interbedded with pale, laminated siltstone, Cùil a' Bhainne, west of the isthmus joining Canna and Sanday. Lens cap *ca*. 8 cm across.



Figure 6-298: Hyaloclastite with basaltic pillows, Cùil a' Bhainne, west of the isthmus joining Canna and Sanday. Pole *ca*. 1 m long.



Figure 6-299: Hyaloclastite with basaltic pillows, Cùil a' Bhainne, west of the tombolo joining Canna and Sanday. Pole *ca.* 1 m long.

Cross-stratification, typical of fluvial systems, is a common feature within many of the sedimentary units, although their variable orientation does not effectively inform on direction of transport. Within the sequence on the east side of Camas Thairbearnais in north-central Canna, gutter casts, comprising silts(tones) and sand(stones) filled with pebble rich sand(stone), indicate the high energy scouring effects of the fluvial system(s), in line with the dominance of conglomerates (Figure 6-300; Figure 6-301; Figure 6-302; Figure 6-303). Thin layers of low-grade coal indicate periods of volcanic quiescence, although possibly geographically localised.



Figure 6-300: Conglomerate-sandstone sequence overlain by a prismatic-jointed basaltic lava, east side of Camas Thairbearnais in north-central Canna. Pole *ca.* 1 m long.

Beta version



Figure 6-301: Gutter cast of pebbly sandstone within laminated sandstone, Camas Thairbearnais in north-central Canna. Pole *ca*. 1 m long.



Figure 6-302: Thin, discontinuous layer of coal overlying laminated sandstones with a lens of conglomerate, all overlain and disrupted by a prismatic-jointed basaltic lava, Camas Thairbearnais in north-central Canna. Pole *ca*. 1 m long.



Figure 6-303: Detail of discontinuous layer of coal overlying laminated sandstones with a lens of conglomerate, all overlain and disrupted by a prismatic-jointed basaltic lava, Camas Thairbearnais in north-central Canna. Pole *ca*. 1 m long.

The Carn a'Ghaill and Beul Lama Sgorr members crop out in the high ground of west and east Canna, comprising prominent basaltic hawaiite and hawaiite lavas that form step-like features (Figure 6-304; Figure 6-305; Figure 6-306). These prismatic jointed lavas, both aphyric and plagioclase porphyritic, are up to 15 m thick and are interbedded with thin basaltic lavas.

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Figure 6-304: Carn a'Ghaill and Beul Lama Sgorr members lavas forming Carn a' Ghaill, east Canna, viewed from west Canna.



Figure 6-305: Carn a'Ghaill and Beul Lama Sgorr members lavas in NE Canna, including the rock pillar of An t-Each, viewed towards the NW from Compass Hill.

Be



Figure 6-306: Detail of the Carn a'Ghaill and Beul Lama Sgorr members lavas in NE Canna, including the rock pillar of An t-Each, viewed towards the NW from Compass Hill. [Photograph courtesy of Ian Williamson]

One compositionally distinct lava crops out at Eilean a' Bhàird, between Canna and Sanday and on the north shore of Canna Harbour, and is attributed to the Eilean a' Bhàird Member. It is distinctively columnar-jointed and of basaltic andesite composition. The stratigraphic position of this lava is difficult to determine, but the underlying conglomerate contains cobbles and boulders of plagioclase-porphyritic hawaiite, like the lavas that cap the sequence on west-central Canna. Consequently, there may be a disconformity separating the Eilean a' Bhàird Member from the underlying Beul Làma Sgorr Member. Similar lavas occur towards the top of the preserved sequence in NW Rum.

6.5.7 Rum

6.5.7.1 Introduction

The Canna Lava Formation crops out in NW Rum, comprising (mildly alkaline) basalt, basaltic hawaiite and hawaiite lavas, tholeiitic icelandite and basaltic andesite lavas, and interbedded clastic sedimentary units, predominantly conglomerates and coarse sandstones. The three outcrops are: Bloodstone Hill, Fionchra-West Minishal, and Orval (Figure 6-307; Figure 6-308; Figure 6-309; Figure 6-310; Figure 6-311).

Beta Version



Figure 6-307: NW Rum from Canna. View towards SE.



Figure 6-308: NW Rum from Canna. View towards SE.

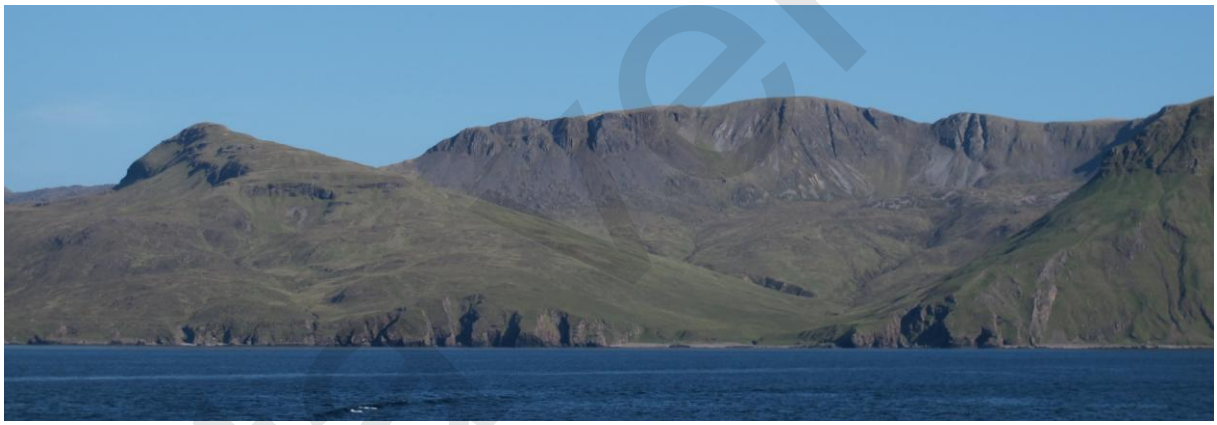


Figure 6-309: Fionchra (left) and Orval (centre) from Canna. View towards SE.

Beta version



Figure 6-310: Sròn an t-Saighdeir from Canna. View towards SE.



Figure 6-311: Bloodstone Hill, Rum and Canna from Coire na Loigh, NW Fionchra. View towards north.

Stratigraphically, four distinct members, from oldest to youngest, are recognised: Lower Fionchra, Upper Fionchra, Guirdal and Orval. (Figure 6-312; Figure 6-313). The sequences on Bloodstone Hill and Fionchra-West Minishal unconformably overlie Late Proterozoic Torridon Group clastic sedimentary rocks (Chapter 2), whereas the Orval sequence unconformably overlies the Paleocene Western Granite of the Rum Central Complex (Chapter 9). Clasts within the conglomerates can be matched with the pre-volcanic 'basement' lithologies on Rum, from which they were derived following the unroofing of the Rum Volcano to expose the central complex. The irregular pre-volcanic and syn-volcanic landscape was repeatedly eroded to produce the clastic sequences interbedded with the lavas, with clasts of (Paleocene) volcanic lithologies and pre-volcanic 'basement' lithologies (Emeleus 1985, 1997).

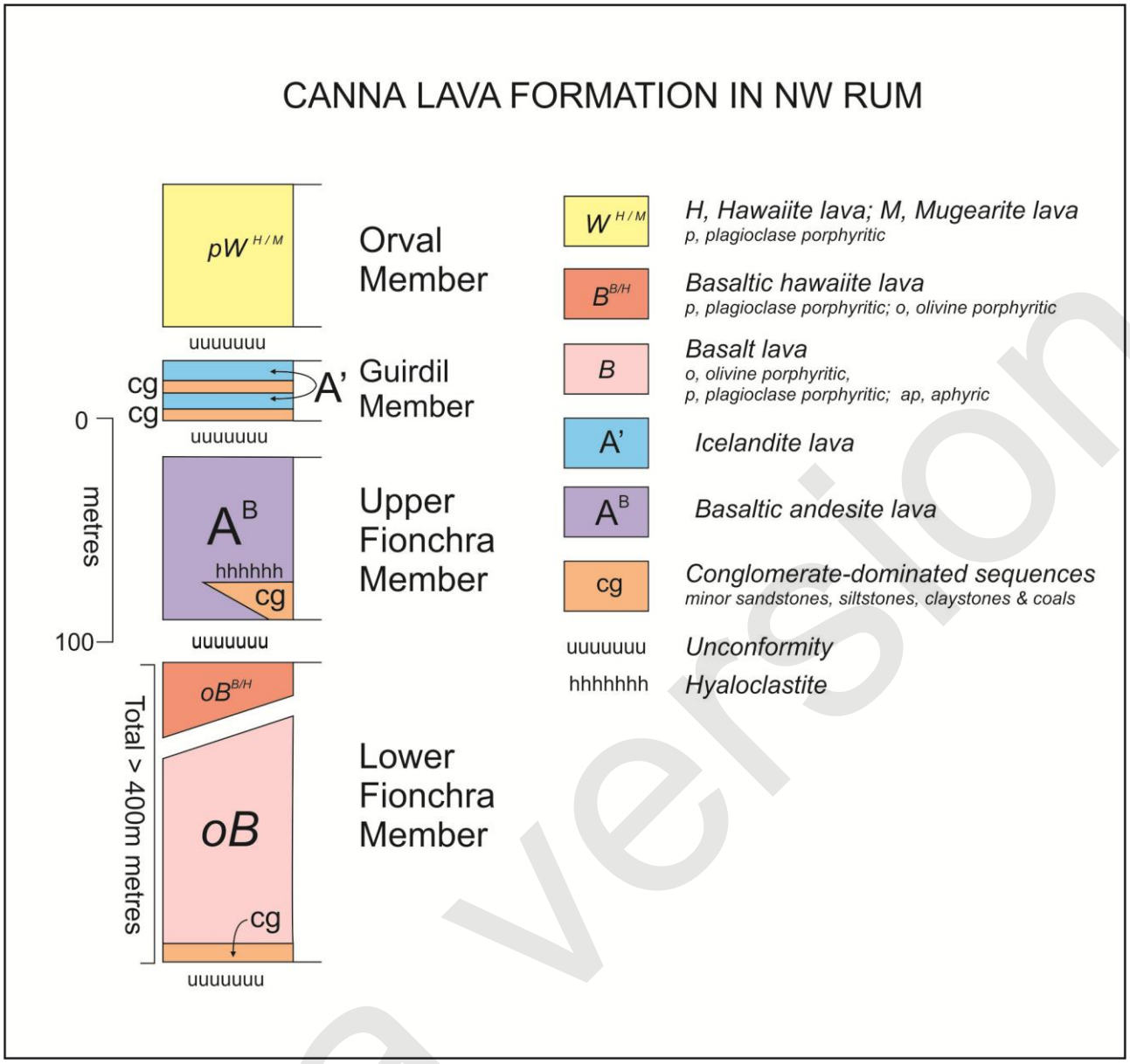


Figure 6-312: Simplified stratigraphic column for the Canna Lava Formation in NW Rum (after Emeleus 1997).

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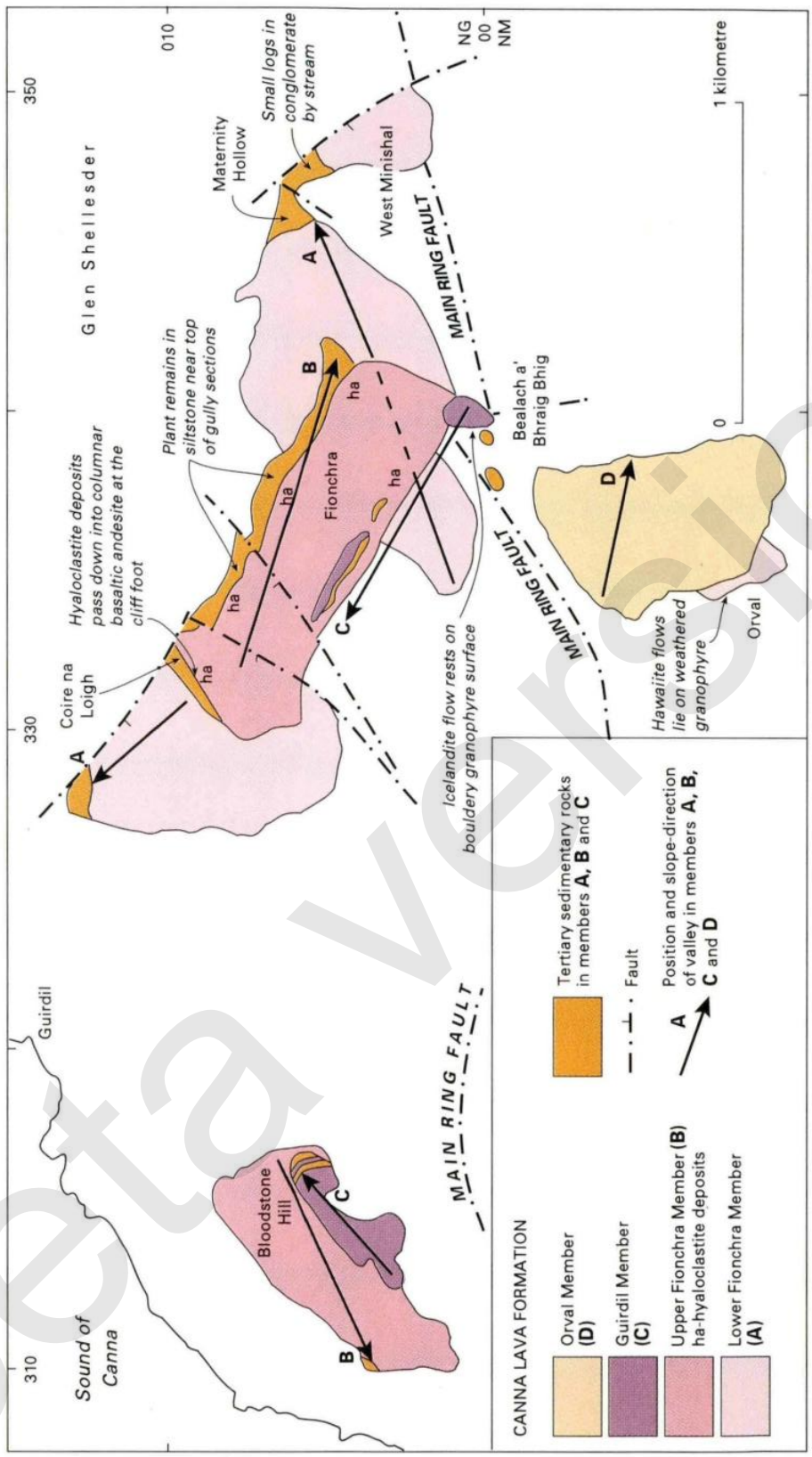


Figure 6-313: Simplified geological map showing the distribution of members of the Canna Lava Formation in NW Rum, and the direction of drainage of the palaeo-valleys (after Emeleus 1985).

Beta version

6.5.7.2 Lower Fionchra Member

The oldest unit of this member comprises *ca*. 50 m of coarse fluviatile conglomerates and sandstones, the latter with thin carbonised fragments of wood up to 1 m in length in the exposures at Maternity Hollow (Figure 6-314; Figure 6-315; Figure 6-316; Figure 6-317). The lavas are up to 10 m thick, although absolute values are difficult to determine due to limited exposure. The oldest lavas are olivine-basalts with microphenocrysts of plagioclase. Towards the top of the preserved sequence, in the valley *ca*. 200 m NE and east of Orval, are basaltic hawaiite lavas, which unconformably overlie an eroded surface of the Paleocene Western Granite (Chapter 9).



Figure 6-314: SE Fionchra from Monadh Mhiltich, NW Rum.



Figure 6-315: NE Fionchra from Maternity Hollow, NW Rum.

Proof version



Figure 6-316: Maternity Hollow conglomerates and Fionchra, NW Rum.



Figure 6-317: Detail of Maternity Hollow conglomerates, NW Rum. Pole *ca.* 1 m long.

The lavas and conglomerates of the member fill palaeo-valleys in the Paleocene land surface, eroded in Torridon Group sandstones and members of the Rum Central Complex. To the east of Fionchra, the conglomerates were deposited in a V-shaped valley, which was subsequently filled by a succession of lavas. The palaeo-valley is truncated to the east by a NNW-trending fault at Maternity Hollow. A remnant of a palaeo-valley wall is preserved in the crags *ca*. 600 m NE of the summit of Fionchra.

6.5.7.3 Upper Fionchra Member

This Upper Fionchra Member forms the upper part of Bloodstone Hill and the ridge of Fionchra (Figure 6-312; Figure 6-313; Figure 6-318; Figure 6-319; Figure 6-320; Figure 6-321; Figure 6-322; Figure 6-323; Figure 6-324). The base of the member is defined by a sequence, up to 30 m thick, of conglomerates, volcaniclastic sandstones and thin plant-bearing siltstones which crops out in stream sections on the north side of Fionchra. The plant remains include delicate leaf and stem impressions. These deposits thin over a short distance southward in Coire na Loigh and only a small outcrop is present in Upper Guirdil, *ca*. 250 m west of the summit of Fionchra. A low mound *ca*. 300 m ENE of the summit of Fioncra exposes a cross-section of valley-fill conglomerate.



Figure 6-318: Bloodstone Hill, capped by lavas of the Upper Fionchra Member, from Coire na Loigh, NW Fionchra.



Figure 6-319: Bloodstone Hill, capped by lavas of the Upper Fionchra Member, from Coire na Loigh, NW Fionchra.

Beta version



Figure 6-320: Upper Fionchra Member basaltic andesite (icelandite) lava, SW Fionchra.



Figure 6-321: Fluviatile conglomerates overlain by (cliff-forming) tholeiitic andesite (icelandite) lava, SW and south Fionchra.



Figure 6-322: Fluviatile conglomerates overlain by (cliff-forming) tholeiitic andesite (icelandite) lava, SW and south Fionchra.

Beta version



Figure 6-323: Fluviatile conglomerates overlain by tholeiitic andesite (icelandite) lava, SW Fionchra.



Figure 6-324: Fluviatile conglomerate overlain by tholeiitic andesite (icelandite), SW Fionchra. Pole *ca.* 1 m long.

Up to 60 m of hyaloclastite breccia with uncommon basalt pillows overlies the sedimentary rocks. At Coire na Loigh, the breccias pass downwards into several metres of strongly columnar-jointed lava which

overlies conglomerate. The breccia is succeeded by up to 80 m of tholeiitic basaltic andesite lavas. A feldspar-phyric basaltic andesite lava occurs low in the succession on the south side of Fionchra and similar material forms the basal sequence on Bloodstone Hill. On Bloodstone Hill, conglomerate is limited to an isolated mass at the base of the lavas, *ca*. 400 m SW of the summit; elsewhere the lavas sit unconformably on weathered Torridon Group sandstone. Small banded agates occur in cavities and green, cryptocrystalline silica flecked with red specks ('bloodstone') fills irregular thin fissures on Bloodstone Hill and at Coire na Loigh. Both materials are common as pebbles on the beach at Guirdil.

6.5.7.4 Guirdil Member

Two icelandite lavas, each overlying a sequence of conglomerate, fill an eastward-draining palaeo-valley, eroded in lavas and Torridon Group sandstones on Bloodstone Hill. A *ca*. 20 m thick icelandite lava and a 1-2 m thick conglomerate form a prominent cliff on the south side of Fionchra (Figure 6-320; Figure 6-321; Figure 6-322; Figure 6-323**)**. This outcrop is part of a lava filling a steep-sided palaeo-valley. A portion of the same lava forms the crags *ca*. 100 m north of Bealach a' Bhraigh Bhig, where it overlies a rounded, boulder-rich surface of the Western Granite.

6.5.7.5 Orval Member

The eastern side of Orval comprises at least three thick lavas of basaltic hawaiite and feldspar-phyric basaltic hawaiite (Figure 6-325; Figure 6-326; Figure 6-327). These lavas are difficult to differentiate, as no intervening laterites are present. They overlie the Western Granite, except in the steep valley NE of Orval, where they abut against a palaeo-valley wall eroded into the uppermost lavas of the Lower Fionchra Member. Harker (1908) considered that the lavas were thermally altered by the Western Granite; however, this has not been confirmed, and the field evidence is clear that all of the lavas of NW Rum post-date the Western Granite (Emeleus, 1985, 1997).



Figure 6-325: Hawaiite lava(s) of the Orval Member on Orval (left) and basaltic lavas of the Fionchra Member on Fionchra (right). View towards the west.

Pre-print version



Figure 6-326: Hawaiite lava(s) on East Orval from Monadh Mhiltich. View towards the west.



Figure 6-327: Hawaiite lava(s) on West Orval from south of Fionchra. View towards the south.

6.5.7.6 Provenance of clasts within the Rum conglomerates

Emeleus (1985) recognised three groups of clasts within the Rum fluviatile conglomerates: Pre-Paleocene country-rocks; rocks that do not match any types now found on Rum; and, rocks from the Rum Central Complex and the lavas of NW Rum.

Clasts of Torridon Group arkosic sandstones and banded gneiss from the Lewisian Gneiss Complex (Chapter 2) are common. The sandstone clasts preserve evidence of thermal metamorphism and only minor alteration is found in a few of the gneiss fragments: they are predominantly fresh hornblende-gneisses. Quartz-dolerite and vesicular tholeiitic basalt fragments are common; the basalt clasts imply the former presence of unevolved tholeiitic lavas on or near Rum that are not preserved. In addition to clasts of tholeiitic basalt, conglomerates high in the sequence contain olivine basalt and feldspar-phyric basaltic andesite clasts, eroded from earlier members of the formation. Material derived from the Rum Central Complex includes: clasts of drusy granophyre and porphyritic rhyodacite - most common and can

Beta version

be large; and, boulders of rhyodacite up to 1.5 m, present in conglomerates beneath the basaltic andesite lavas on Bloodstone Hill.

Fragments of bytownite-troctolite are also identified, although gabbro is rare and peridotite is absent. The absence of clasts of peridotite is most likely due to the instability, physically and chemically, of the rock-type in a high-energy fluviatile environment. Peridotite is also almost absent from the boulders in the Pleistocene raised beach deposits of Rum. Summarily, the occurrence of a wide range of igneous rock-types that make up the clast population of the conglomerates that match rocks presently on Rum infers that the Rum Volcano underwent deep erosion during the Palaeocene to unroof and expose the Rum Central Complex.

6.6 The Srath na Crèitheach, Kilchrist and Belig deposits, Skye

6.6.1 Introduction

Pyroclastic and associated (volcani)clastic rocks occur throughout central Skye in close spatial association with the central complex, and range from material that is unequivocally intrusive, to deposits that were clearly laid down under subaerial and subaqueous conditions. Historically, the term agglomerate has been used to embrace a significant proportion of these rocks (Harker 1904), but, in line with present-day terminological usage, is essentially redundant, as a high proportion of the larger fragments in these rocks are non-magmatic in origin, hence the preferred usage of the non-genetic term breccia.

Three significant outcrops of fragmental rocks occur in central Skye, intimately associated with intrusions of the Cuillin Intrusive Centre and the Red Hills granites (Chapter 9): (i) Srath na Crèitheach; (ii) Kilchrist; and, (iii) north of Belig. The outcrop in Srath na Crèitheach comprises interbedded coarse-grained and fine-grained fragmental deposits in close association with large masses of gabbro (Jassim & Gass 1970). The Kilchrist outcrop occupies the ground south of Beinn Dearg Bheag in Strath, between Cnoc nam Fitheach and Creagan Fitheach. Here, the dominant materials are poorly- to unstratified, coarse-grained fragmental rocks with a diverse lithological range of angular to sub-rounded blocks, including various Mesozoic and older lithologies, various types of basalt and dolerite of presumed Paleocene age, together with crystal-rich and crystal-poor silicic ignimbrites, and thin, bedded silicic tuffs (Bell 1985). The relationships of these rocks are obscured in part by a suite of younger hybrid intrusions, the so-called Kilchrist Hybrids (Chapter 9), and a large granite intrusion, the Beinn na Caillich Granite, to the north (Chapter 9). The outcrop north of Belig, forming the higher part of Coire Choinnich, is intruded by granite and the Marscoite Suite Ring-dyke of the Western Red Hills Intrusive Centre (Chapter 9). It comprises unstratified, sub-angular to rounded blocks of various lithologies, including gabbro and dolerite, similar to that of the nearby intrusions of the Cuillin Intrusive Centre, Torridonian and Mesozoic sedimentary rocks and amygdaloidal basalt, similar to the country-rocks into which the intrusive centre was emplaced, and granite and various quartz and feldspar porphyritic silicic igneous lithologies that do not match any nearby outcrops (Bell 1966).

The shapes of both the Srath na Crèitheach and Kilchrist outcrops are very strongly influenced by the distribution of adjacent younger intrusions and, consequently, caution needs to be exercised when considering the origin of these rocks. In addition, younger ring faults may have (significantly) controlled the outcrop pattern. At Srath na Crèitheach, the granites to the north are younger, whereas the gabbros to

Beta version

the west, south and east are older. At Kilchrist, the Kilchrist Hybrids, a suite of mixed-magma intrusions (Chapter 9) to the west and east are younger, as is the granite to the north. However, the contact between the fragmental rocks and the Cambro-Ordovician Durness Group dolostones between Coire Beithe and Buaile nan Aodan, although poorly exposed, appears to take the form of an unconformity.

Fragmental rocks spatially and genetically associated with the Rum Central Complex are dealt with in Chapter 9.

6.6.2 Srath na Crèitheach

The deposits that crop out at the northern end of Loch na Crèitheach, in Srath na Crèitheach, occupy an area of *ca.* 2 km^2 and have an estimated vertical extent of at least 200 m and a 'stratigraphic' thickness of around 450 m (Jassim & Gass 1970) (Figure 6-328). These rocks were originally described by Harker (1904), who concluded that they represent a lens of agglomerate caught up in the gabbros of the Cuillin Intrusive Centre. In contrast, Jassim (1970) and Jassim & Gass (1970) suggested that this mass of fragmental material represents some form of vent infill that was deposited under subaerial and subaqueous conditions. At least twelve large 'slabs' of gabbro related to, or derived from in some way, the nearby Cuillin Intrusive Centre, are spatially associated with these clastic rocks. The descriptions presented below are largely influenced by the studies of Jassim (1970) and Jassim & Gass (1970).

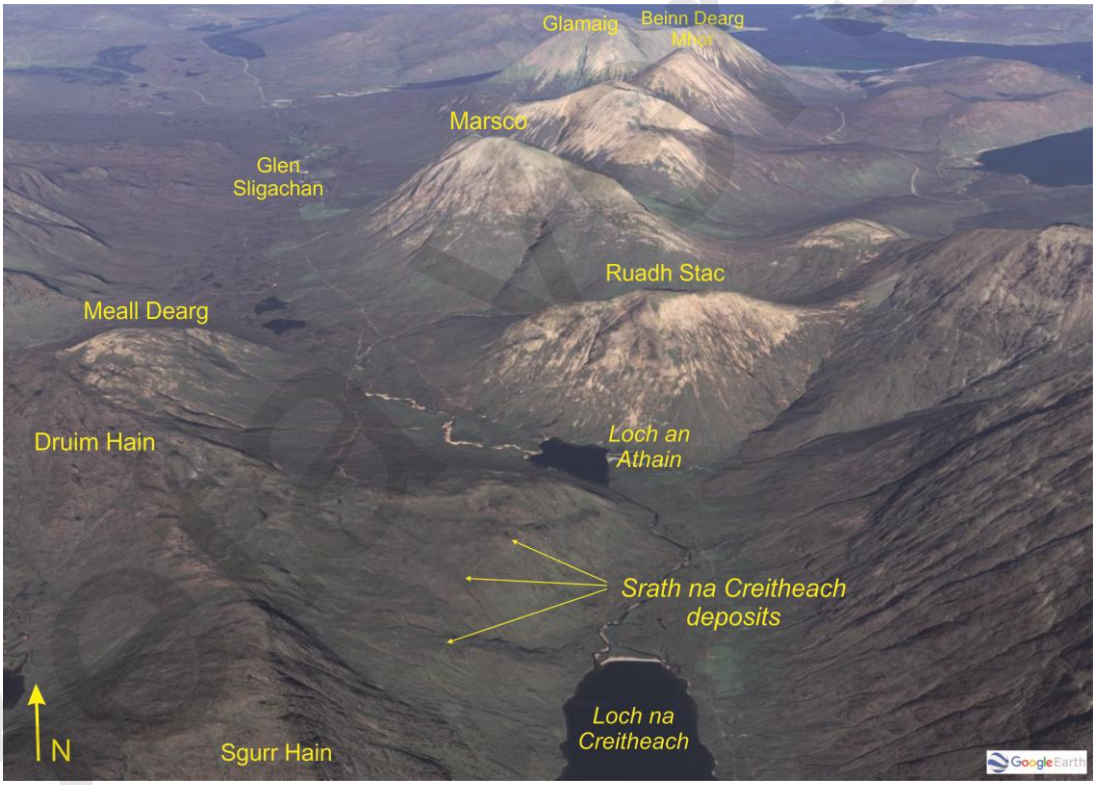
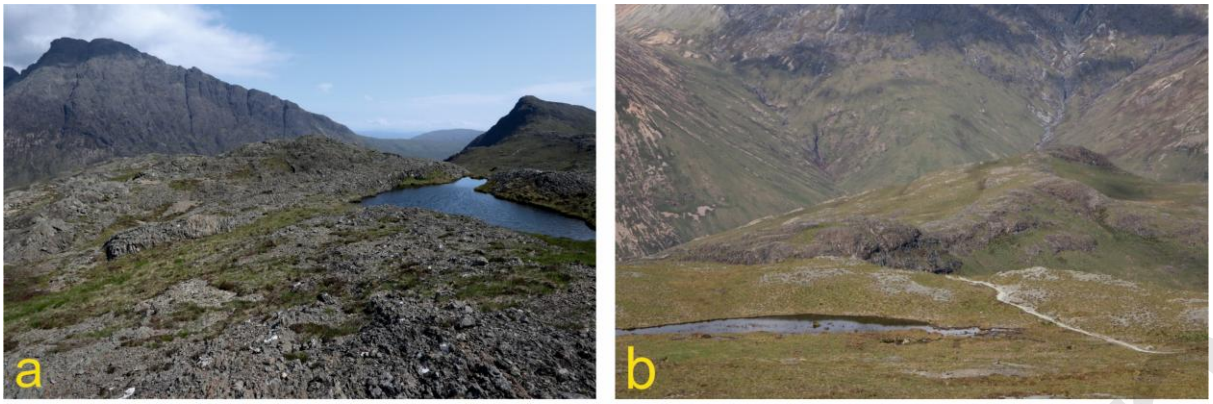
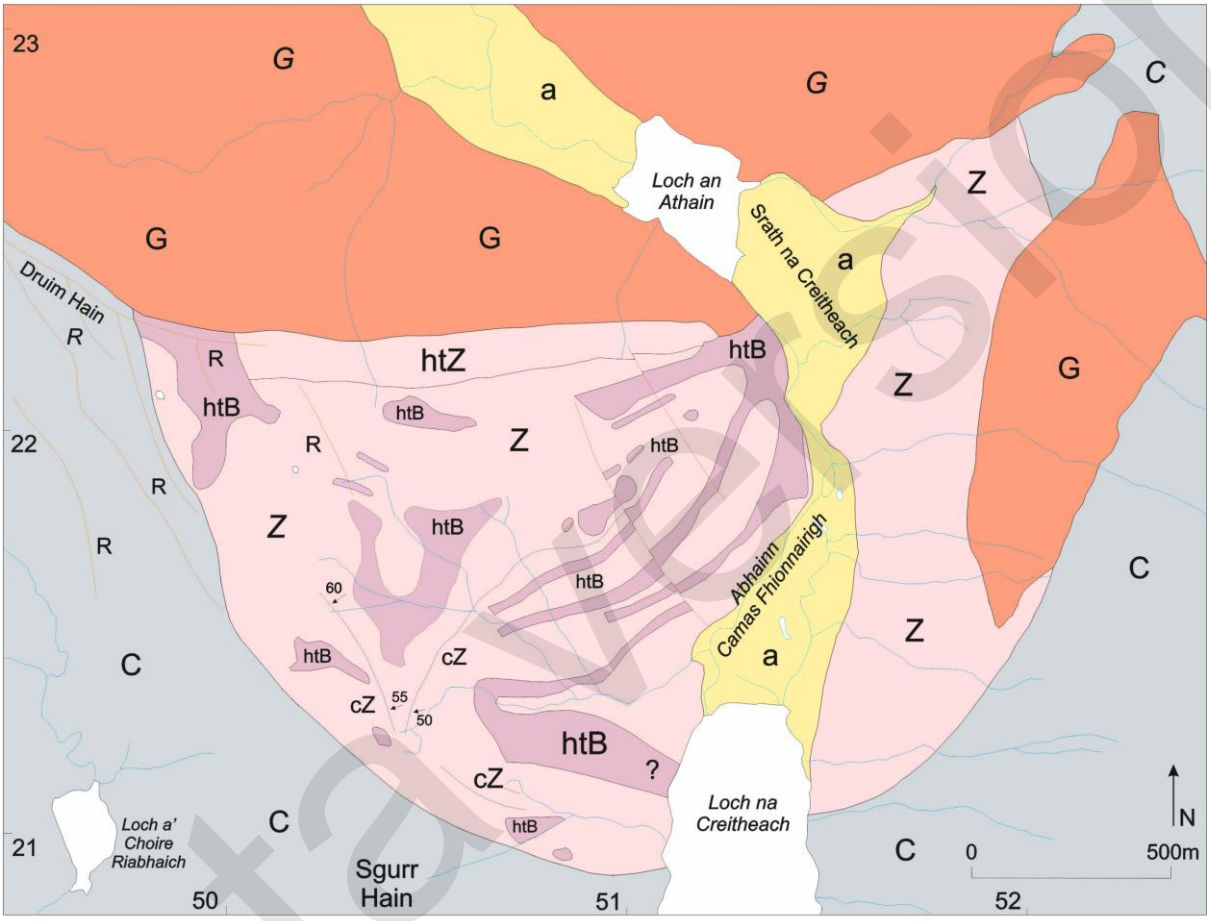


Figure 6-328: Oblique Google Earth© image of Srath na Crèitheach area.

Along their western and southern margins, the Srath na Crèitheach fragmental rocks are in contact with layered gabbros of the Cuillin Intrusive Centre. This boundary has been identified as a steeply inclined, arcuate ring-fault, in part because of the cross-cutting termination of the layering of the gabbros. The northern and eastern margins are against granites of the younger Srath na Crèitheach Intrusive Centre (Figure 6-329).

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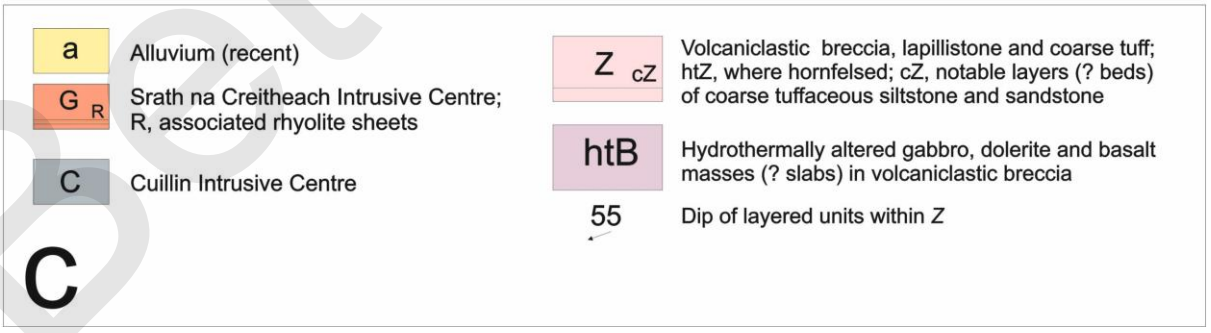


Figure 6-329: Field views of the Srath na Crèitheach area: (a) the western end of the outcrop, viewed east towards Blà-bheinn; and, (b) the eastern end of the outcrop, viewed east towards Srath na Crèitheach; and, (c) a simplified geological map of the Srath na Crèitheach area (after Jassim & Gass 1970).

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The dominant breccia comprises uncommon sub-angular to sub-rounded metre-sized blocks and common sub-angular decimetre- to cm-sized fragments of various basic igneous rocks, basalt, dolerite and gabbro, set in a dark, chlorite-rich matrix of mm-sized comminuted material of similar type (Figure 6-330). Blocks of peridotite are also present, but are much less common, as are angular to sub-angular blocks of stratified volcaniclastic sandstone or tuff and plagioclase-porphyritic trachyte. Apparently-laterally continuous inclined beds, up to 10 m thick, of mm-scale, stratified volcaniclastic sandstone and siltstone, or tuff, are also present and are composed of approximately equal proportions of crystals of plagioclase and rock fragments.



Figure 6-330: Typical coarse volcaniclastic breccia from the Srath na Crèitheach area, SE of Meall Dearg. Coin *ca.* 24 mm across.

Within the same outcrop are several large gabbro (*s.l.*) 'slabs', ranging in length between 40 m and 900 m, which tend to stand proud of the surrounding breccia, and with typically sharp contacts. Strictly, most of the slabs are olivine-bytownite gabbros with megacrysts of calcic plagioclase (*ca*. An_{85}) and, petrographically, are very similar to the Outer Bytownite Gabbros of the Cuillin Intrusive Centre (Chapter 9) that crop out to the south and east. Layering is identified in one slab and is discordant to the margin of the slab. Brecciation and fragmentation of the slabs are common.

Jassim & Gass (1970) have outlined the events that they consider best explain the nature and distribution of the Srath na Crèitheach deposits. First, a (large) volcanic vent broke through to the Earth's surface, disrupting the basic layered rocks of the Cuillin Intrusive Centre and the overlying lavas of the main plateau sequence. Subsequently, a caldera formed, and further explosive activity gave rise to subaerial and shallow subaqueous deposits of tuff, lapilli-tuff and agglomerate (their term) within this volcanic depression. Collapse of gabbro slabs and fragments of basaltic lava from the vent walls caused their entrapment within the sequence. Surface reworking of the tuffs then occurred. Jassim & Gass (1970) estimate that subsidence of the material by as much as 750-1,000 m subsequently took place along marginal ring-faults. Granites of the Srath na Crèitheach Intrusive Centre (Chapter 9) were then emplaced.

An alternative scenario, suggested here, is that the various coarse-grained unsorted fragmental rocks, described above, are of epiclastic origin, essentially sedimentary breccias, formed by weathering and erosion of various volcanic basaltic lithologies, with localised low-energy subaqueous sedimentation of volcanic debris in shallow bodies of water, most likely ephemeral lakes, to produce the stratified volcaniclastic sandstones and siltstones. The mechanism by which the gabbro slabs were incorporated into these deposits is, however, unclear. It is possible that some type of vent-forming phase transported fragments of these rock-types to the surface, where they were subsequently incorporated into subaerial deposits by gravitational slumping on an irregular topography.

6.6.3 Kilchrist

The Kilchrist outcrop is dominated by polylithic breccias and comprise a heterogeneous assemblage of lithologies covering an area of *ca*. 2 km^2, in places relatively poorly exposed, with a stratigraphic thickness of at least 300 m (Figure 6-331; Figure 6-332; Figure 6-333; Figure 6-334). Access is better in the Spring, Autumn and Winter due to the aggressive and rampant vegetation growth in the Summer. An unambiguous base to the sequence is not exposed, although is tentatively identified as the inferred boundary with the Cambro-Ordovician Durness Group dolostones (Chapter 2) between Coire Beithe and Buaile nan Aodan, SE of Beinn na Caillich. Five main lithologies are recognised: (i) polylithic breccia (Figure 6-335; Figure 6-336; Figure 6-337; Figure 6-338); (ii) basaltic tuff; (iii) silicic tuff; (iv) ignimbrite (Figure 6-339); and, (v) masses of brecciated rhyolite (Figure 6-340).

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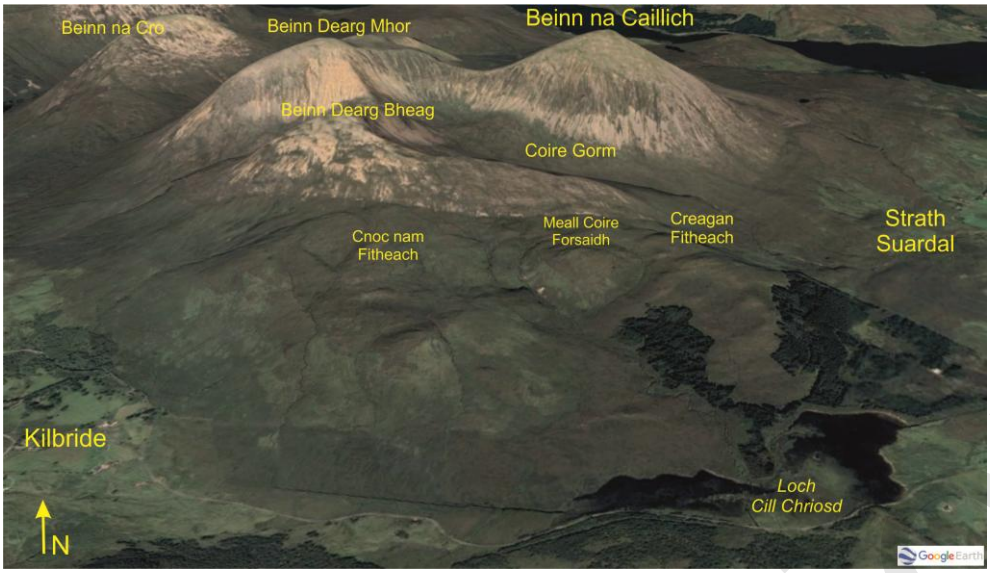


Figure 6-331: Oblique Google Earth© image of the Kilchrist area. View is towards the NW.

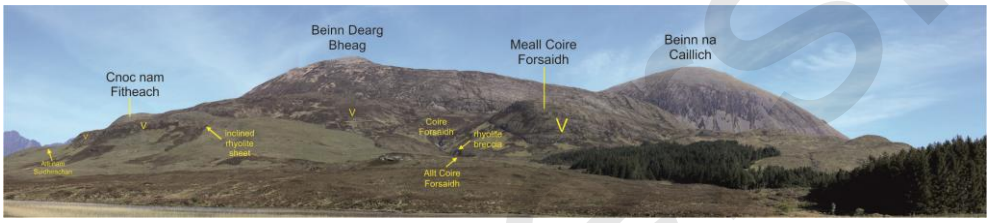


Figure 6-332: Field view of the Kilchrist area. Much of the area is dominated by weakly stratified to massive polylithic volcaniclastic breccia (V). Also labelled are a rhyolite sheet and a mass of rhyolite breccia. Views is towards the north from the Broadford-Kilbride Road.



Figure 6-333: Meall Coire Forsaidh, Kilchrist, composed predominantly of weakly stratified polylithic breccia.

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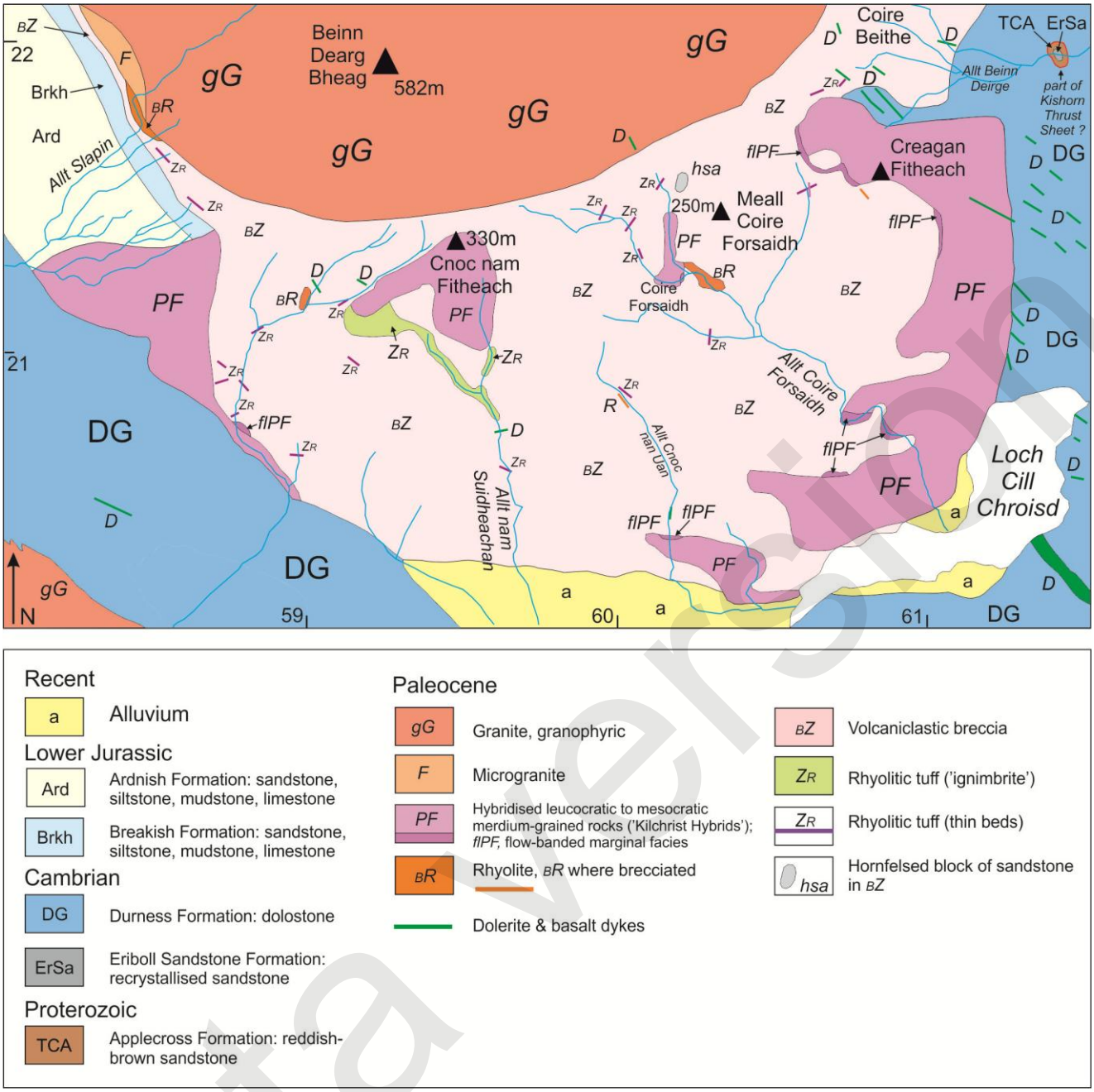


Figure 6-334: Simplified geological map of the Kilchrist area, Strath, Skye.

(**i**) The most abundant rock-type is coarse, unbedded, polylithic breccia (Figure 6-336). It is very poorly sorted and has been hydrothermally altered by the nearby younger intrusions: the Kilchrist Hybrids and the large Beinn na Caillich Granite to the north (Chapter 9). Only the least-altered material will be described.

Blocks that comprise the breccia are randomly distributed, range from sub-angular to rounded, and vary in size, up to several metres across. Block-types include: Torridonian sandstone and shale, Cambro-Ordovician sandstone/quartzite and dolostone, Jurassic limestone, sandstone and siltstone (Chapter 3), Paleocene basalt (including amygdaloidal and plagioclase-porphyritic variants), dolerite, gabbro, rhyolite, tuff (including ignimbrite), granite, vitrophyre, and pre-existing coarse- and fine-grained pyroclastic and volcaniclastic materials. Locally outcropping gneiss of the Lewisian Gneiss Complex (Chapter 2) is not recognised as blocks in the breccia.

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Figure 6-335: Typical coarse-grained, polylithic, volcaniclastic breccia in the Kilchrist area. Hammer *ca.* 30 cm long.



Figure 6-336: Typical coarse-grained, polylithic, volcaniclastic breccia in the Kilchrist area. Coin *ca*. 24 mm across.



Figure 6-337: Typical coarse-grained, polylithic, volcaniclastic breccia in the Kilchrist area. Pole *ca*. 1 m long.

Typically poor exposure limits any evidence of stratification, although subaqueous or subaerial deposition and reworking and erosion surfaces are evident, for example, north of Loch Cill Chriosd, in the Allt Coire Forsaidh, a 0.5 m thick, reddened interval within the breccia consists of lithic clasts, typically up to 5 cm across, set in a fine-grained, red-brown, volcaniclastic matrix, interpreted as the product of subaerial weathering and is, essentially, a poorly developed palaeosol or laterite.

Block-supported and matrix-supported macro-textures occur throughout the breccia, indicating that the transport and depositional processes were highly variable. The general lack of stratification is taken as an indication that transportation was by some form of hyper-concentrated or debris flow mechanism.

A (mega-)block of Cambrian sandstone (quartz arenite/quartzite) (Chapter 2), with shattered material at its margin, crops out north of Meall Coire Forsaidh and measures at least 60 m by 30 m (Figure 6-338).

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Figure 6-338: Planar surface of a (mega-)block of Cambrian sandstone (quartz arenite/quartzite) within the Kilchrist breccias, NW of Meall Coire Forsaidh, Kilchrist. Pole *ca*. 1 m long.

(**ii**) Intercalated with the breccia are numerous thin layers of relatively fine-grained basaltic volcaniclastic material, with examples of grading from breccia to sand grade material over intervals of up to several tens of centimetres. These volcaniclastic sandstones are dull grey-green and contain sub-angular to sub-rounded basaltic clasts up to 10 mm across. Erosional surfaces are also identified.

(**iii**) Closely associated with the breccia and the beds of finer-grained basaltic volcaniclastic material are thin beds of silicic tuff or tuffaceous sandstone. Over twenty distinct exposures have been identified (Bell 1985), although some may be lateral equivalents. Typically, they are less than 2.5 m thick (and commonly less than 1 m). Except for some of the deposits exposed in the crags south of Beinn Dearg Bheag, the tuffs/sandstones are visible and accessible only where cut by the numerous small unnamed streams that dissect the area.

These pale deposits commonly have irregular, weathered tops that, in some cases, are overlain by dark, fine-grained material, mainly volcaniclastic siltstones and sandstones. Bedding may be discerned in some instances, for example, two deposits NE of Meall Coire Forsaidh, whereas in others there is very little vertical (stratigraphic) variation in grain-size. The silicic character of these deposits is only readily identified in the least-altered units, where wispy fragments of rhyolitic material, up to 5 mm long and with curved margins, are set in a fine-grained, clastic matrix. Angular crystals of quartz and, less commonly, alkali feldspar and plagioclase, are present, as are small xenoliths of various types of country-rock.

(**iv**) Ignimbrites in the Kilchrist district were first recorded by Ray (1960, 1966), who described material from two localities in the Allt nan Suidheachan - Cnoc nam Fitheach area (Figure 6-339). Both were interpreted to be intrusive, forming marginal facies of a micro-adamellite intrusion. This intrusion is

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interpreted here as the product of magma mingling, one of the Kilchrist Hybrids (Chapter 9), involving basaltic and rhyolitic magmas, and is considered here to being unrelated to the ignimbrites. Both ignimbrite outcrops are interpreted by Bell (1985) to be extrusive.



Figure 6-339: Detail of the ignimbrite in the Allt nan Suidheachan area, with typical foliation (banding, or eutaxitic fabric) and angular xenoliths. Coin *ca*. 24 mm across.

The Cnoc nam Fitheach outcrop consists of four distinct sheets, with a total thickness of *ca*. 4.5 m, and is exposed in a small gully that flows SE into the Allt nan Suidheachan. This ignimbrite is relatively crystal-rich, has a strong eutaxitic fabric, and dips at an angle of *ca*. 35° towards the NW. The deposit has a distinct base, with bedding defined by a eutaxitic fabric dipping at a very low angle towards the NE/north. This lower boundary is erosional, with the underlying breccia showing a slight amount of (Paleocene) lateritic weathering. Low-angle brittle faults, discordant to the fabric of the ignimbrite, cause the dip of the fabric to increase, up-section. These faults, of unknown displacement, have also acted as hydrothermal fluid conduits, causing extensive alteration of the adjacent ignimbrite for distances of a few centimetres. The resulting pale green, homogeneous rock has very few recognisable primary characteristics. At the top of this deposit, the fabric of the ignimbrite is distorted, with the formation of small, detached folds and cusp-shaped masses. Directly above this deposit is coarse breccia.

The ignimbrite exposed in the Allt nan Suidheachan is also inclined, but at a higher angle, *ca*. 60°, to the NE. Essentially, it is a large slab of material 120–130 m in length and between 10 and 20 m thick. The fiammé that define the eutaxitic fabric of this ignimbrite have very high aspect ratios (length:thickness), not uncommonly 25:1, or more, indicating extreme compaction and welding.

Both ignimbrites contain xenoliths and crystals. Xenolith types include most of the pre-Paleocene lithologies that crop out within the district and are present as blocks within the breccias (see above). In

the case of the crystals, there is abundant sanidine, perthitic alkali feldspar and quartz. The glass component of the ignimbrites is commonly dark brown (less often dark green) and is much altered and devitrified.

(**v**) Three discrete masses of brecciated quartz-alkali feldspar micro-porphyritic rhyolite are identified (Figure 6-340), all with obscure field relationships (due to a lack of good exposure) to the surrounding and volumetrically-dominant coarse, unbedded, polylithic breccias: (**a**) in a stream west of Cnoc nam Fitheach, *ca*. 85 m by 35 m; (**b**) within the Allt Coire Forsaidh, south of Meall Coire Forsaidh, *ca*. 115 m by 40 m, forming an obvious pale scar clearly visible from afar and consisting of distinctly pale-weathering (grey-green) brecciated rhyolite with individual angular fragments typically a few centimetres across, rarely up to a decimetre; and, (**c**) in the stream bed and gorge walls of the Allt Slapin, consisting of apparently vertical masses of brecciated rhyolite, a few metres wide, with conspicuous banding and spherulitic texture within the fragments.



Figure 6-340: Brecciated quartz-alkali feldspar micro-porphyritic rhyolite from the main exposure (scar) in Coire Forsaidh, east of the stream confluence. The clasts and the matrix material are hydrothermally altered, with the development of secondary chlorite, epidote and clay. Coin *ca*. 24 mm across.

All of these outcrops of brecciated rhyolite are hydrothermally altered, with the development of secondary chlorite, epidote and clay. In the Allt Coire Forsaidh outcrop, veins and disseminated crystals of pyrite have been altered to various iron oxides and hydroxides.

From the descriptions presented above, it is evident that a range of volcanic and volcanic-related products of the Kilchrist district can be readily distinguished and that it is not appropriate to group these

highly variable accumulations under the essentially redundant term, agglomerate. Furthermore, the overall field relationships at Kilchrist can be better explained in terms of an incomplete ring-dyke intrusion of the Kilchrist Hybrids that partially define the outcrop (shape) of the breccia and other spatially associated lithologies. The gross character of the different types of material suggests that surface processes - subaqueous and/or subaerial - have dominated their mode of deposition and that within-vent processes, as suggested by Harker (1904), were not involved.

The numerous silicic tuffs, for example, together with the ignimbrites, are evidently extrusive/eruptive in form and their deposition would have been on relatively irregular surfaces, strongly controlled by the voluminous breccia accumulations. The aspect ratios of the fiammé in the ignimbrites and the wispy rhyolitic fragments in the tuffs also suggest large degrees of compaction. Rheomorphism, in the form of secondary mass flowage, can occur in such deposits, and deposition on slopes is a critical aspect of features such as flow folds, cusps and slump structures, resulting in (lava-like) ignimbrites. The preserved material is at most mere fragments of originally considerably larger (laterally and vertically) deposits.

Walker (1975) proposed that a significant feature in the positioning and development of individual intrusive centres throughout the province, including Skye, was the emplacement of silicic diapirs high in the crust at an early stage. Such diapirs are believed important because they would considerably influence the development of fragmental material, i.e. breccias. Walker (1975) suggested that some of the so-called 'vent agglomerates' of Harker (1904) may in fact have been derived from shattered country-rock from roof-zones, together with chilled and disrupted material from the upper parts of these diapirs (see below). Due to updoming, this material would exist at an elevated/shallow position in the crust and through erosion would be readily subjected to surface reworking processes. Thus, the agglomerates of Harker (1904), referred to here as polylithic breccias, are essentially sedimentary in character.

The lack of (Lewisian) gneiss fragments in the breccias possibly provides some evidence as to how high within the crust the top of such a silicic diapir was able to rise. The absence of this rock-type suggests that the zone of brecciation above the diapir was structurally above the gneiss at its pre-granite intrusion level within the crust.

Other occurrences of rhyolitic rocks, with somewhat ambiguous field relationships, occur along the margin of the Beinn na Caillich Granite north of the Kilchrist deposits and are exposed in the Allt Slapin and as far around the margin of the granite as the west-flowing tributaries of the Allt an t-Sratha Bhig in Srath Beag.

6.6.4 Belig

The breccias that crop out north of Belig were first described in detail and interpreted by Harker (1904) (Figure 6-341; Figure 6-342; Figure 6-343; Figure 6-344), who identified their contact with the basaltic lavas that form the summit of Belig as dipping towards the south and that the fragmental rocks, referred to as agglomerates, being intruded by younger granites. The dominant block types, typically sub-angular to sub-rounded and up to 0.5 m across, are of basalt, dolerite and gabbro, together with a lesser amount of, but locally abundant, granite and quartz-porphyritic felsite, all set in a dark chlorite-rich matrix of comminuted material (Figure 6-344). Stratification is absent, although, locally, layers of grey silicic tuff is recognised.

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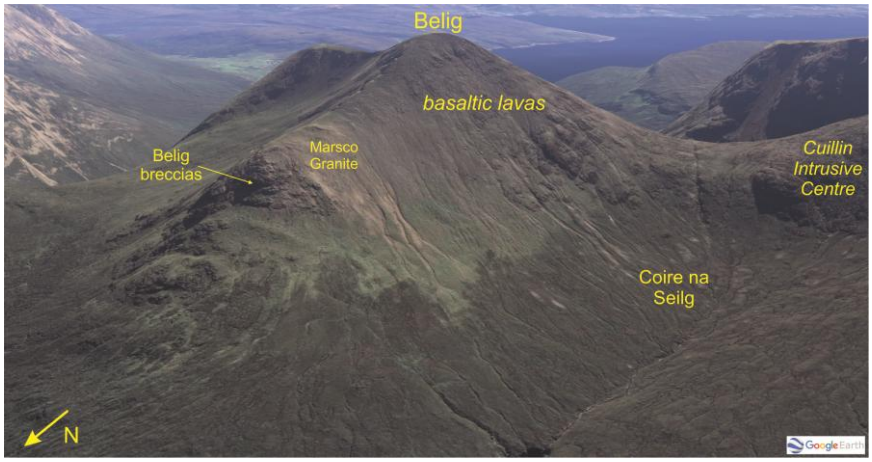


Figure 6-341: Oblique Google Earth© image of the Belig area. View towards the SE.

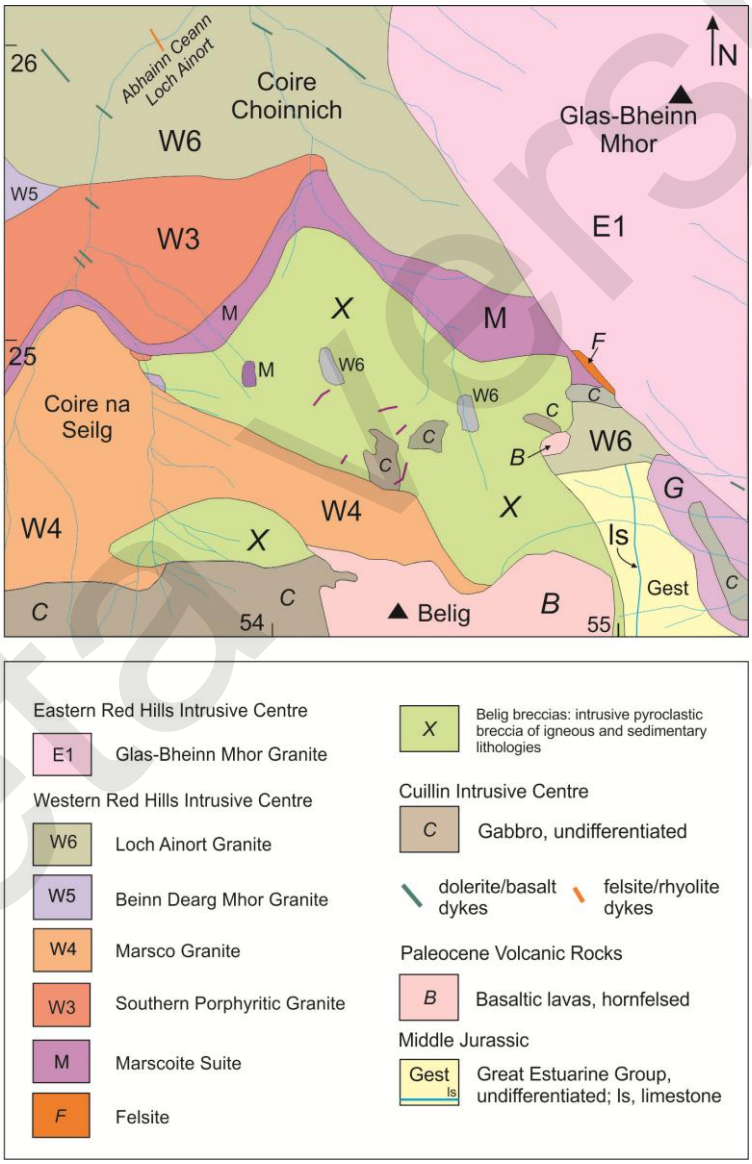


Figure 6-342: Geological map of the Belig area illustrating the distribution of the breccias.

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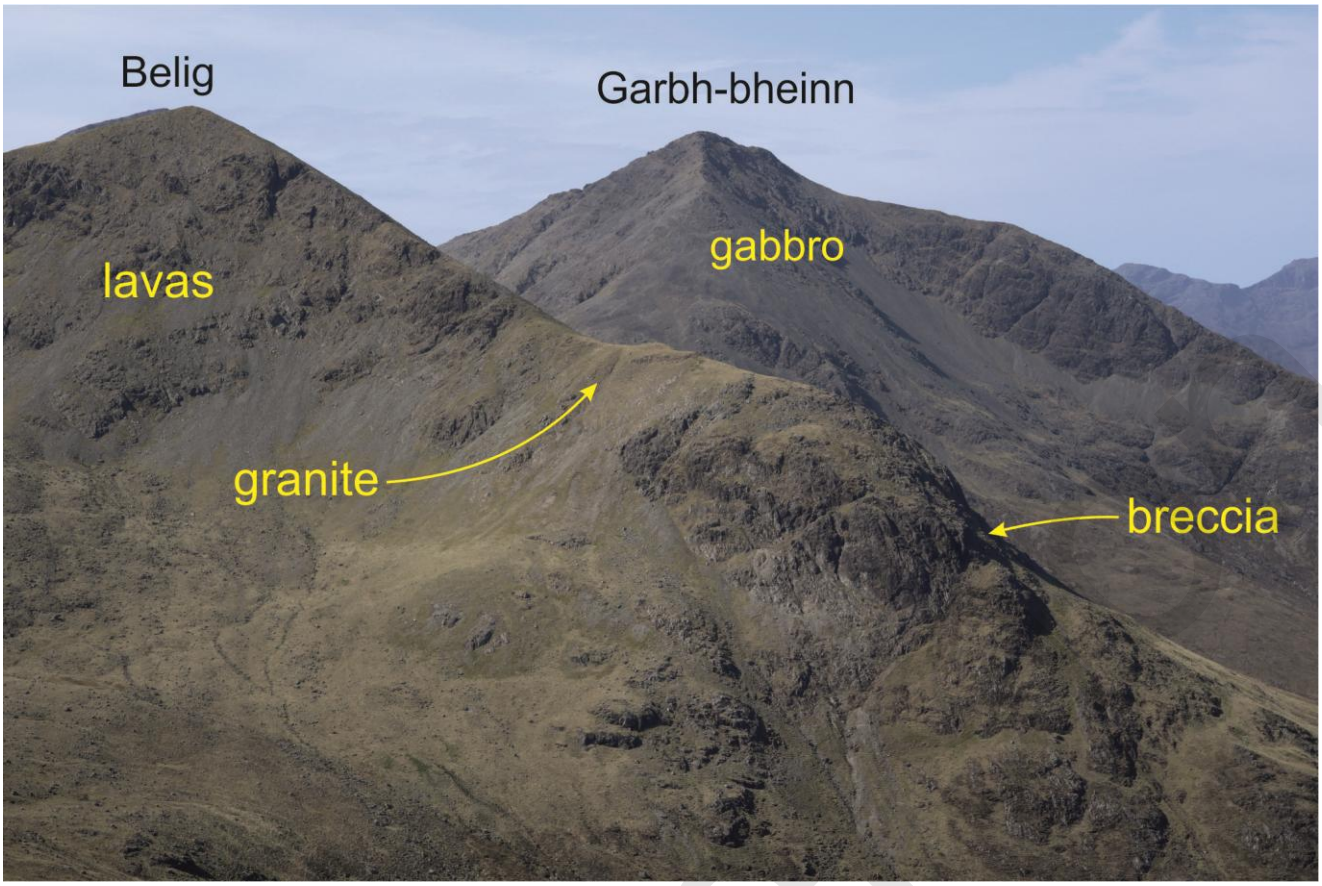


Figure 6-343: Field view of the Belig area. View towards the SW from the southern end of the Glas-Bheinn Mhòr ridge.

Bell (1966) re-examined these rocks and his description does not differ significantly from that of Harker (1904). Blocks of Torridonian and Mesozoic sedimentary rocks are recognised, the former only occurring *in situ* at least 5 km distant from the breccia outcrop. Some of the (mega-) blocks of gabbro and basalt are up to 50 m across and are brecciated.

Bell (1966) interpreted the Belig breccias as the product of disruption and fragmentation of pre-existing lithologies by degassing/devolatilisation of silicic magma(s) during their emplacement into the shallow crust, including (genetically related) early crystallised felsite/granite. Fluidization caused rounding of previously formed fragments. In essence, these outcrops are interpreted as 'explosion' breccia(s) (see above).

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Figure 6-344: Typical unstratified Belig breccia, with sub-angular to sub-rounded clasts/fragments up to 0.5 m across of pale granite and quartz-porphyritic felsite, dark basalt, dolerite and gabbro, all set in a dark chlorite-rich matrix of comminuted material. Coin *ca*. 24 mm, pole *ca*. 1 m.

6.7 Eigg Lava Formation

6.7.1 Introduction

The volcanic sequences on the islands of Eigg and Muck are attributed to a separate sequence, not obviously related to the lavas of neither the Mull nor the Skye lava fields. Reasons for defining these rocks as a distinct formation, the Eigg Lava Formation, include: apparent distinctly different isotopic ages (Chapter 5), although, remarkably, there is still no coherent, province-wide data set for the igneous units of the Hebridean Igneous Province; the Skye Lava Field contains abundant thin sedimentary units, especially in NW Rum and on the islands of Canna and Sanday, a feature largely absent from the Eigg Lava Formation (Figure 6-345); and, the volcanic rocks on Eigg and Muck are intruded by a NW-SE -trending dyke swarm, which is intruded by the Rum Central Complex, which, in turn, is older than the lavas of the Skye Lava Field in NW Rum, which unconformably overlie the central complex.

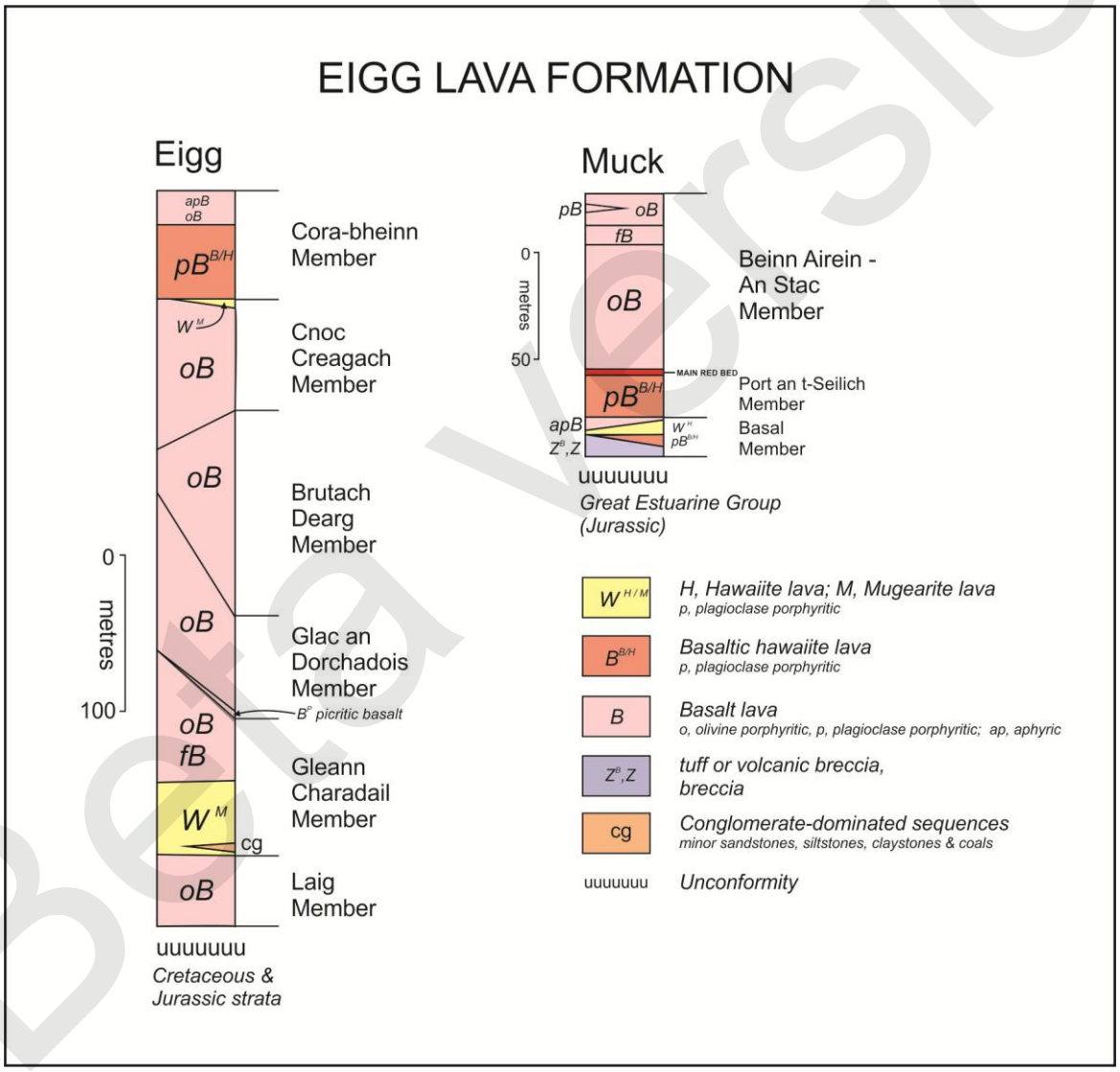


Figure 6-345: Lava stratigraphy of the Eigg Lava Formation on Eigg and Muck.

Unconformably overlying the lava sequence in south Eigg is a lava-like, rhyodacite ignimbrite, which is detailed separately, below (Figure 6-346).

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6.7.2 Eigg

The lavas and rare sedimentary units from Clach Alasdair in central-west Eigg, east, around northern Eigg, to Kildonnan, unconformably overlie the Cretaceous Strathaird Limestone Formation and the Jurassic Great Estuarine Group (Chapter 3). The unconformity is largely concealed by landslips and drift (Figure 6-347; Figure 6-348; Figure 6-349; Figure 6-350; Figure 6-351; Figure 6-352; Figure 6-353; Figure 6-354; Figure 6-355; Figure 6-356). The oldest part of the succession is typically thin tuffs and volcaniclastic sandstones and siltstones, for example at Dalian Thalasgair and Bealach Clith, although they are several metres thick in the Allt Ceann a'Gharaid. Lavas overlie Cretaceous rocks at Clach Alasdair. The main succession consists of various types of basaltic lava, with several prominent mugearite lavas, especially *ca*. 50 m above the base of the Formation. The distinctive feldspar-phyric lavas of the Cora-bheinn Member include several of basaltic hawaiite composition.

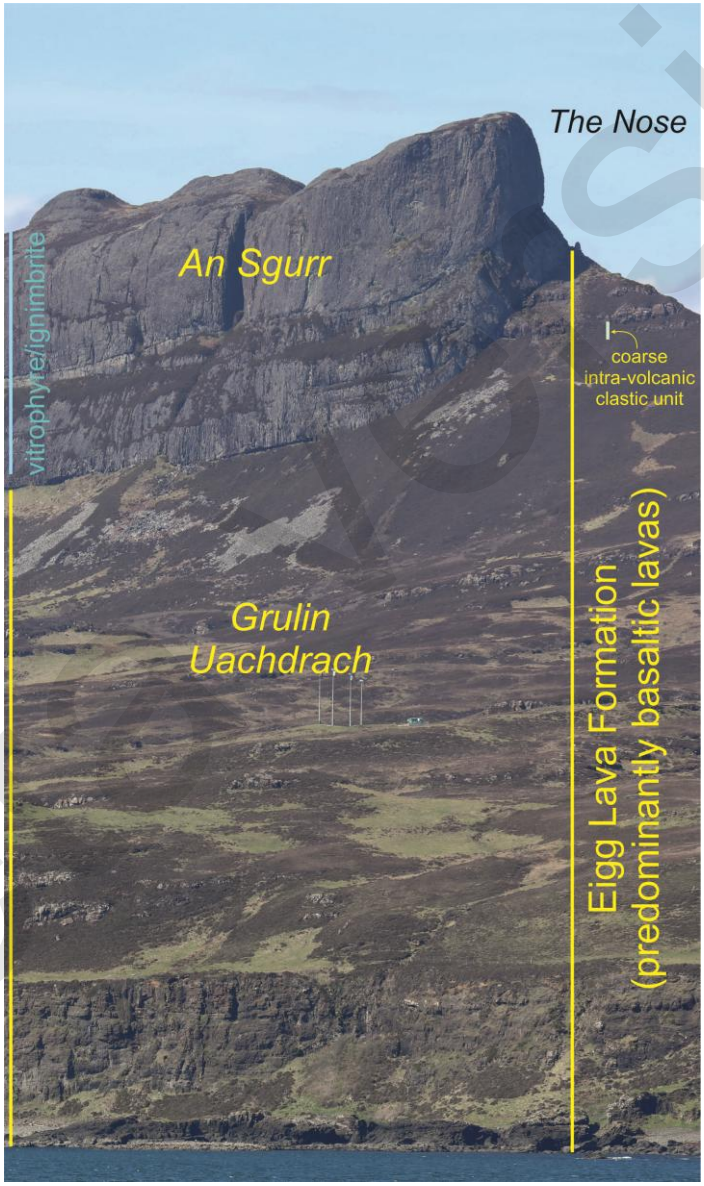


Figure 6-346: Distribution of the Eigg Lava Formation in south Eigg, overlain by the Sgùrr of Eigg Pitchstone Formation (vitrophyre/ignimbrite). Note good exposures restricted to the coastal cliffs and the cliffs below An Sgùrr.

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Figure 6-347: Lava sequence of north Eigg from Galmisdale, SE Eigg.

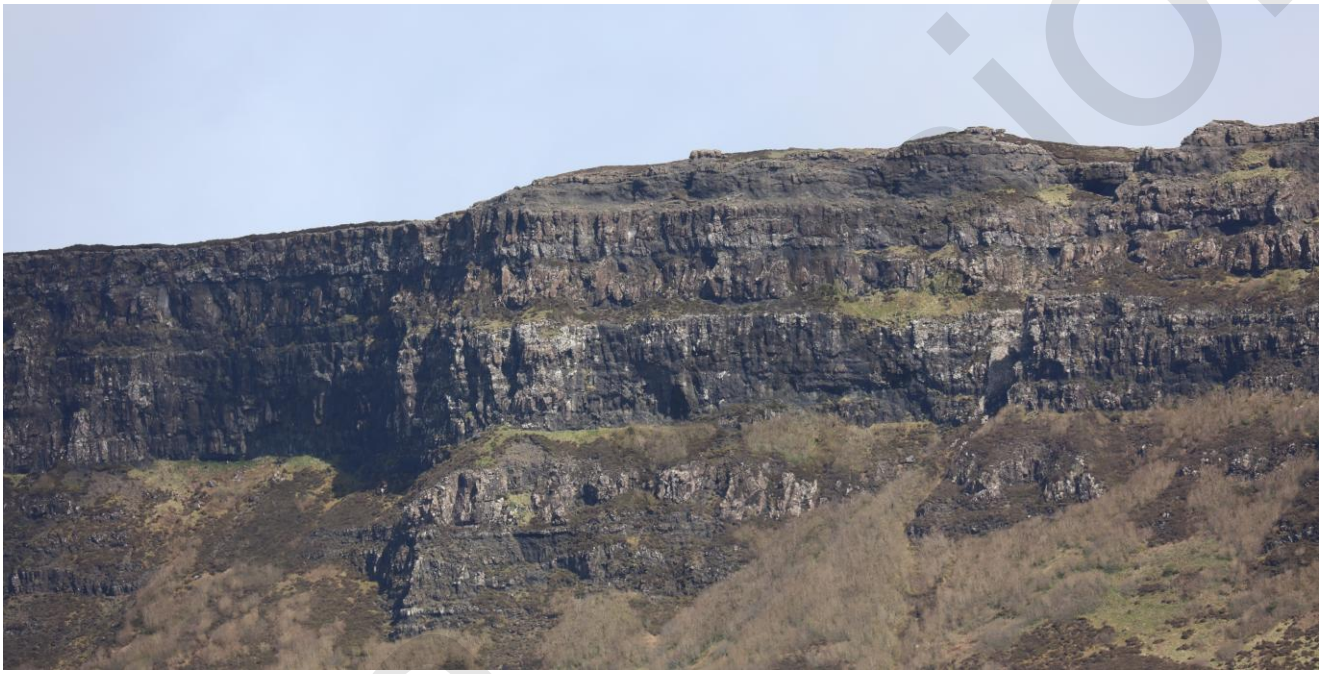


Figure 6-348: Interbedded compound and simple basaltic lavas of the Eigg Lava Formation, Sgorr an Fharaidh, Cleadale, Eigg.

Beta version



Figure 6-349: Lava sequence of north Eigg, forming the landslip escarpment of A' Chuagach, from Bay of Laig.

Beta version



Figure 6-350: Prominent ridge of the Sgùrr of Eigg vitrophyre/ignimbrite, unconformably overlying clastic sedimentary rocks (obvious at eastern end of outcrop), overlying basaltic lavas of the Eigg Lava Formation along the coast at Gruilin Uachdrach, south Eigg.



Figure 6-351: Detail of basaltic lavas of the Eigg Lava Formation along the coast of Gruilin Uachdrach, south Eigg.

As elsewhere in the HIP, the terraced character of the present-day landscape is the result of differential erosion between the resistant-to-erosion cores of the lavas and their more easily weathered and eroded tops and bases (Figure 6-352); the lavas are commonly separated by thin beds of red laterite formed during Paleocene weathering. The *ca*. 400 m thick sequence dips towards the SW at *ca*. 3°, with individual lavas commonly between 5 and 10 m thick, although some are over 20 m thick, for example a massive columnar-jointed olivine-basalt lava that forms Druim an Aoinidh (Figure 6-353) and the base of the cliffs north from Kildonnan; at the latter locality, the columnar joints are locally highly irregular rather than in the typical vertical attitude. Individual lavas can be traced over several kilometres, for example a grey-weathering mugearite lava near the base of the succession (Figure 6-354; Figure 6-355; Figure 6-356). Two

or more lavas totalling 30 m thickness, but generally about 10-15 m thick, crop out from the coast 500 m west of Clach Alasdair, around northern Eigg, to the old (Clanranald) pier, although partially obscured by landslips (Chapter 13). This distinctive marker interval links the lava successions of northern and SW Eigg. Amygdaloidal tops to the lavas are common and, with some thin lavas, for example in the cliffs east of Uamh Fhraing, are amygdaloidal throughout. Amygdale minerals include: calcite, quartz, analcime, chabazite, stilbite and mesolite, with less common thomsonite, gyrolite and apophyllite (Harker 1908).



Figure 6-352: Inland escarpment of lavas of the Eigg Lava Formation, east Eigg, from Bealach Clìth, north.



Figure 6-353: Prominent columnar-jointed olivine-basalt lava, Druim an Aoinidh, Kildonan, SE Eigg.

Preview version



Figure 6-354: Profile of the east side of Eigg, with prominent ridge of vitrophyre/ignimbrite at south (An Sgùrr, left-hand side) and, within the main inland escarpment cliffs, a distinctive, laterally extensive, grey-weathering mugearite lava.



Figure 6-355: Grey-weathering mugearite lava, Eigg Lava Formation, within escarpment at Struidh, east Eigg.



Figure 6-356: Detail of grey-weathering mugearite lava, Eigg Lava Formation, within escarpment at Struidh, east Eigg.

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The uncommon sedimentary beds interbedded with the Eigg lavas are soft, fine-grained, bright red or orange-red mudstones; some may be of tuffaceous origin. Similar beds are more common on Muck (see below). An impersistent pebbly conglomerate overlies the reddened, brecciated top of a mugearite lava on the foreshore west of the old pier.

6.7.3 Muck

The lavas and basal sedimentary rocks on Muck overlie poorly exposed limestones of the Jurassic Kilmaluag Limestone Formation at Camas Mór (Chapter 3) (Figure 6-345; Figure 6-357; Figure 6-358; Figure 6-359; Figure 6-360; Figure 6-361; Figure 6-362), where the contact is complicated by faults. The lava-dominated sequence forms a gently NNW-dipping (<3°) succession *ca.* 140 m thick and is intruded by the NNW-trending Muck Dyke Swarm and by numerous small NW-to NNW-trending normal faults (Figure 6-361).



Figure 6-357: Muck from An Sgùrr, Eigg. View towards the SW.



Figure 6-358: Muck from the Sound of Eigg. View towards the SW.



Figure 6-359: Lava sequence, Beinn Airein, south muck.

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Figure 6-360: Detail of lava sequence, Beinn Airein, south Muck.



Figure 6-361: Lava sequence and basaltic dyke, Torr nam Fitheach, south Muck.



Figure 6-362: Volcaniclastic claystone, Sgorr nan Laogh, Camas Mòr, Muck. Pole *ca.* 1 m long.

The lowest lavas on Muck are typically impersistent and of feldspar-phyric basaltic hawaiite, basalt and mugearite, which form the Basal Member (Figure 6-345). A possible flow front occurs at Camas Mòr, where the basal basaltic hawaiite lava terminates abruptly to the west, 100 m SE of Torr nam Fitheach, and at Port an t-Seilich, where a mugearite lava ends abruptly to the east. The Basal Member is overlain by four lavas of feldspar-phyric basaltic hawaiite, with labradorite phenocrysts up to 2 cm in length. These lavas constitute the Port an t-Seilich Member and crop out intermittently along the south coast of Muck. They are succeeded by the Beinn Airein-An Stac Member, which consists largely of olivine-basalt lavas, except for a feldspar-phyric basaltic lava on Beinn Airein and an impersistent feldspar-phyric olivine-basalt lava on Eilean nan Each. This member occupies most of Muck and gives rise to the strong trap topography of the island.

Bright red and orange-red mudstones are common in the lavas in the cliffs of Beinn Airein and in the shore sections east of Sgorr nan Laogh (Figure 6-363; Figure 6-364; Figure 6-365; Figure 6-366). Some of these mudstones grade (downwards) into reddened flow tops and originated by *in situ* lateritic weathering, whereas many form discrete, bedded layers that suggests they are water-lain tuffs (Emeleus *et al.* 1996). The Main Red Bed in the cliff *ca.* 100 m NE of Sgorr nan Laogh is one such example and another occurs east of Port Mòr (Figure 6-363), where a 20-30 cm thick red bed (Figure 6-365) overlies the reddened, brecciated pahoehoe top of a basalt lava (Figure 6-363; Figure 6-365) exposed at the top of the wave-cut platform. This red bed consists of euhedral crystals and angular fragments of fresh sanidine, sodic clinopyroxene, biotite and titanite, and a fine-grained, felsic rock with attached fragments of these crystals, set in a very fine-grained, deep red, ferruginous matrix.

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Figure 6-363: Bright red Port Mòr tuff overlying reddened brecciated top of a pahoehoe lava, SE Muck. Pole *ca*. 1 m long.



Figure 6-364: Lava lobe invading underlying Port Mor Tuff (bright red) and brecciated top of a pahoehoe lava, SE Muck. Pole *ca*. 1 m long.



Figure 6-365: Bright red Port Mòr tuff overlying reddened brecciated top of a pahoehoe lava, SE Muck. Lens cap *ca*. 8 cm across.



Figure 6-366: Bright red Port Mòr tuff, SE Muck. Lens cap *ca*. 8 cm across.

On Eigg, a somewhat similar reddened tuff containing sanidine and pale green clinopyroxene fragments occurs in a disused quarry near the manse, south of Cnoc a' Breacnaich. The crystals and lithic clasts suggest derivation from a nearby, explosive eruption of peralkaline trachytic magma at an early stage in the construction of the Eigg Lava Formation; however, no comparable lava has been identified amongst the lavas on Muck or Eigg.

6.7.4 Camas Mòr Breccia

A coarse sedimentary breccia crops out beneath the boulders on the shoreface at the east end of Camas Mòr (Figure 6-367; Figure 6-368; Figure 6-369; Figure 6-370; Figure 6-371). The exposures occur over *ca.* 200 m to the west of a prominent cliff of feldspar-phyric basaltic hawaiite lava. The breccias are intruded by the northern tip of the Camas Mòr gabbro dyke and by several NNW-trending dolerite dykes.



Figure 6-367; Camas Mòr, south Muck, with Paleocene basaltic lavas overlying the Camas Mòr breccia and Middle Jurassic Duntulm and Kilmaluag formations strata, all cut by Paleocene dolerite dykes. View towards the SE.

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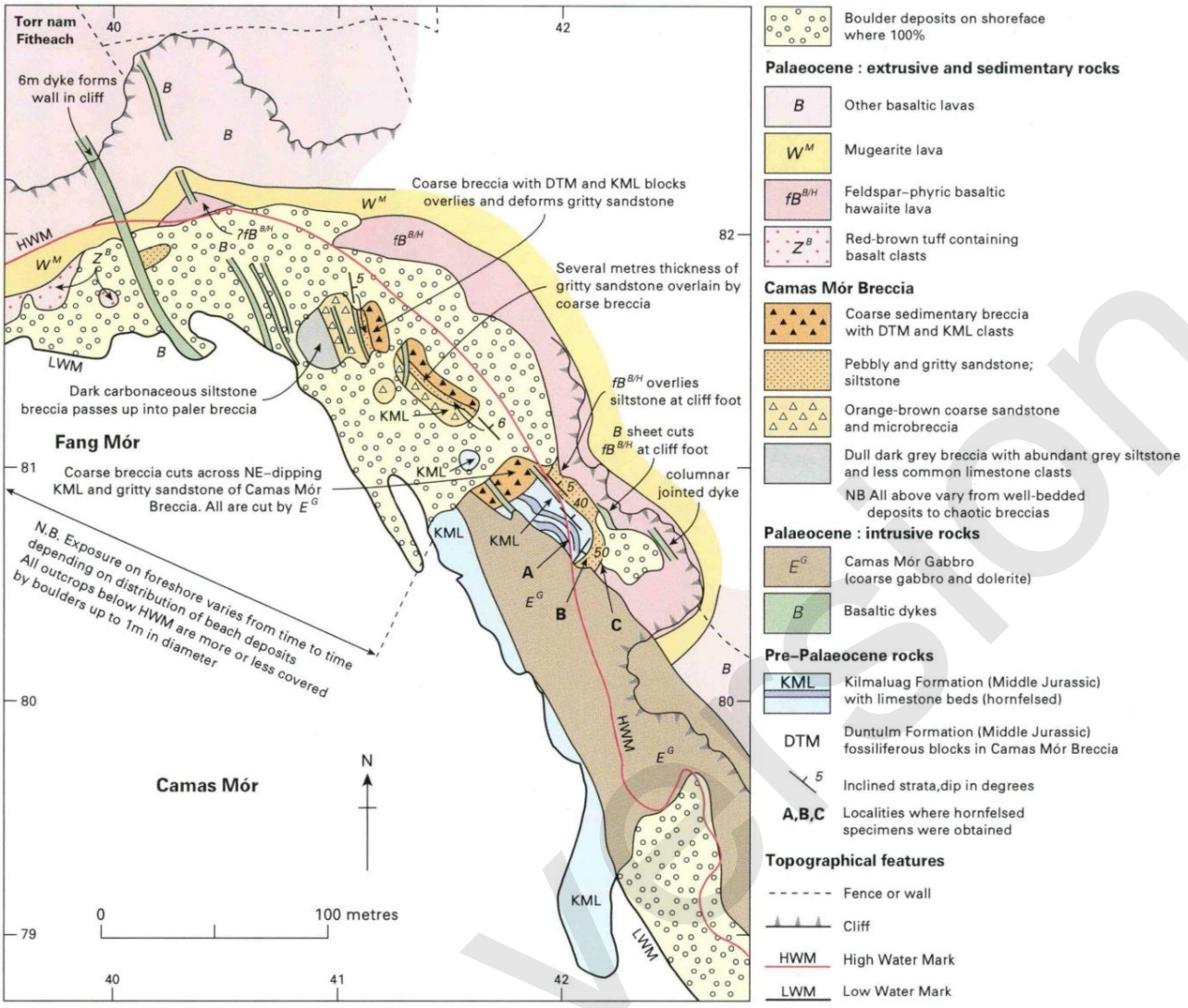


Figure 6-368: Geological map of east Camas Mòr, Muck, showing the distribution of the Camas Mòr Breccia and adjacent rocks (after Emeleus 1997).

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Figure 6-369: Camas Mòr breccia, south Muck. Pole *ca.* 1 m long.



Figure 6-370: Camas Mòr breccia, south Muck. Lens cap *ca.* 8 cm across.

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Figure 6-371: Rounded dolerite block and shattered block of limestone, Camas Mòr breccia, south Muck. Pole *ca*. 1 m long.

The character of the breccia changes from west to east. The most westerly exposures comprise black, carbonaceous siltstone in the breccia matrix. The clasts, typically 20-30 cm across, are predominantly grey, marly limestone, limestone with close packed bivalves and a brown argillaceous limestone with bivalves (from the Middle Jurassic Duntulm Formation) (Chapter 3). To the east, the matrix contains progressively less siltstone and becomes cream, pale grey or orange; locally, there is a distinct carious weathering. These clasts are more typically centimetre-sized and appear slightly sorted and stratified, with a north-easterly dip (*ca*. 10-20°). Small scarps of well-bedded, coarse-grained pebbly rock occur, and their bedding is deformed where they underlie large blocks of limestone from the Duntulm and Kilmaluag formations. Bedded, pebbly sandstones near the end of the Camas Mòr gabbro dyke pass up into siltstones, overlain by a feldspar-phyric basaltic hawaiite lava to the east. No igneous material has been identified in the breccia and the adjoining lavas are undisturbed. Both the lavas and the gritty rocks have been thermally altered by the gabbro dyke and the sedimentary rocks are folded close to the dyke (

Figure **6-367**). Breccia that truncates bedding in the gritty sandstone is in turn cut by the gabbro.

The breccias are of uncertain age. They post-date the Kilmaluag Formation but appear to underlie the basal Paleocene lavas. They crop out close to reddish brown basaltic tuffs, but the contact between the breccias is not exposed. The breccia could have formed during phreatic explosions induced by the gabbro as it intruded wet, incompletely lithified Jurassic rocks (cf. England *et al*. 1993). This interpretation is supported by the relicts of a stratigraphical succession in the breccia at the eastern end of the bay.

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However, had this occurred it is difficult to see how the lavas remained intact and, furthermore, complicated contact relationships would be expected between the gabbro dyke and the sedimentary rocks. On balance the evidence indicates that the breccias predate the basal lavas on Muck.

6.7.5 Rum

A narrow strip of metamorphosed basalt, interpreted as lava, occurs in the Main Ring Fault and extends for *ca.*1 km at *ca.* 250 m OD on the SE slopes of Beinn nan Stac (Figure 6-372). Within this faulted sliver, the lavas overlie the Lower Jurassic Broadford Beds with a landscape unconformity (Smith 1985). Altered lava also crops out on the NE side of Dibidil.

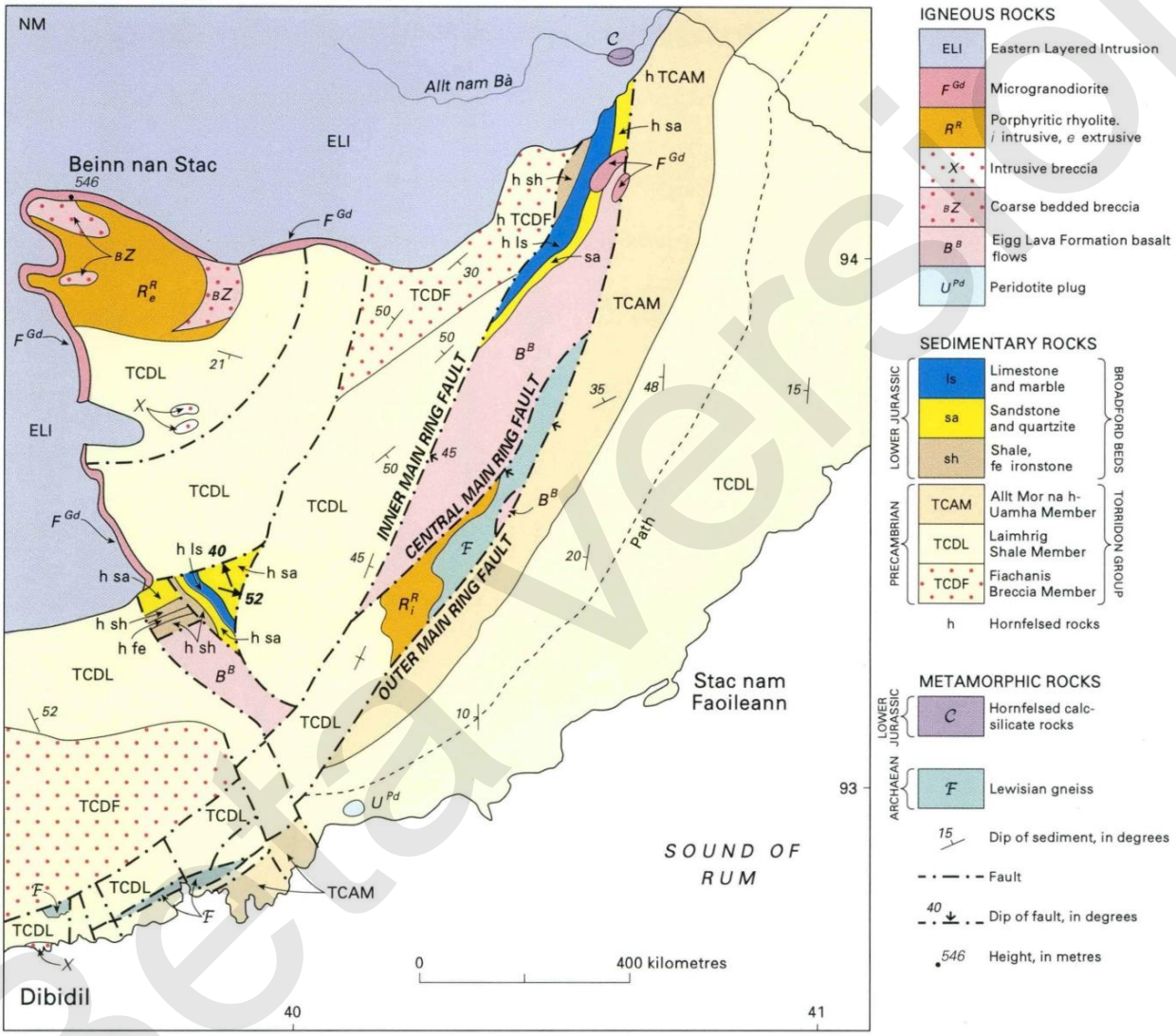


Figure 6-372: Geological map illustrating components of the Main Ring Fault at Allt nam Bà and on the SE side of Beinn nan Stac, Rum (after Emeleus 1997).

These lavas are composed of tough, splintery, dark grey basalt due to thermal metamorphism by the adjacent gabbro. Scattered plagioclase micro-phenocrysts are present, and the rock is commonly amygdaloidal. It is difficult to distinguish individual lavas, and no inter-lava red beds have been identified. All the lava material shows signs of fracturing and small-scale dislocations commonly off-set feldspar phenocrysts. These much-altered rocks resemble mylonites locally and all show signs of crushing.

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6.7.6 The Sgùrr of Eigg Formation

6.7.6.1 Introduction

The ignimbrite of the Sgùrr of Eigg Formation forms the magnificent ridge of An Sgùrr (Figure 6-373; Figure 6-374; Figure 6-375; Figure 6-376; Figure 6-377; Figure 6-378) and its origin has been the subject of much controversy. Geikie (1871, 1897) referred to the rock as a pitchstone, lithologically better described here as a vitrophyre (but see below), that filled an ancient river valley eroded in the underlying lavas and floored by fluviatile conglomerates, whereas Harker (1906, 1908) concluded that the vitrophyre/pitchstone intruded the lavas and interbedded sediments, a view he reiterated in a discussion of a contribution by Bailey (1914), who supported Geikie's interpretation. Allwright (1980) supported the extrusive interpretation of Geikie and Bailey and mapping of the base of the vitrophyre demonstrates that the body fills a system of palaeo-valleys (Figure 6-378). The valleys appear to have drained westwards since their floors are at higher levels in the east than in the west, even after allowing for the likelyhood that the general low (*ca*. 5°) SW dip of the lavas postdates eruption of the unit.



Figure 6-373: An Sgùrr, Eigg, viewed towards the west.

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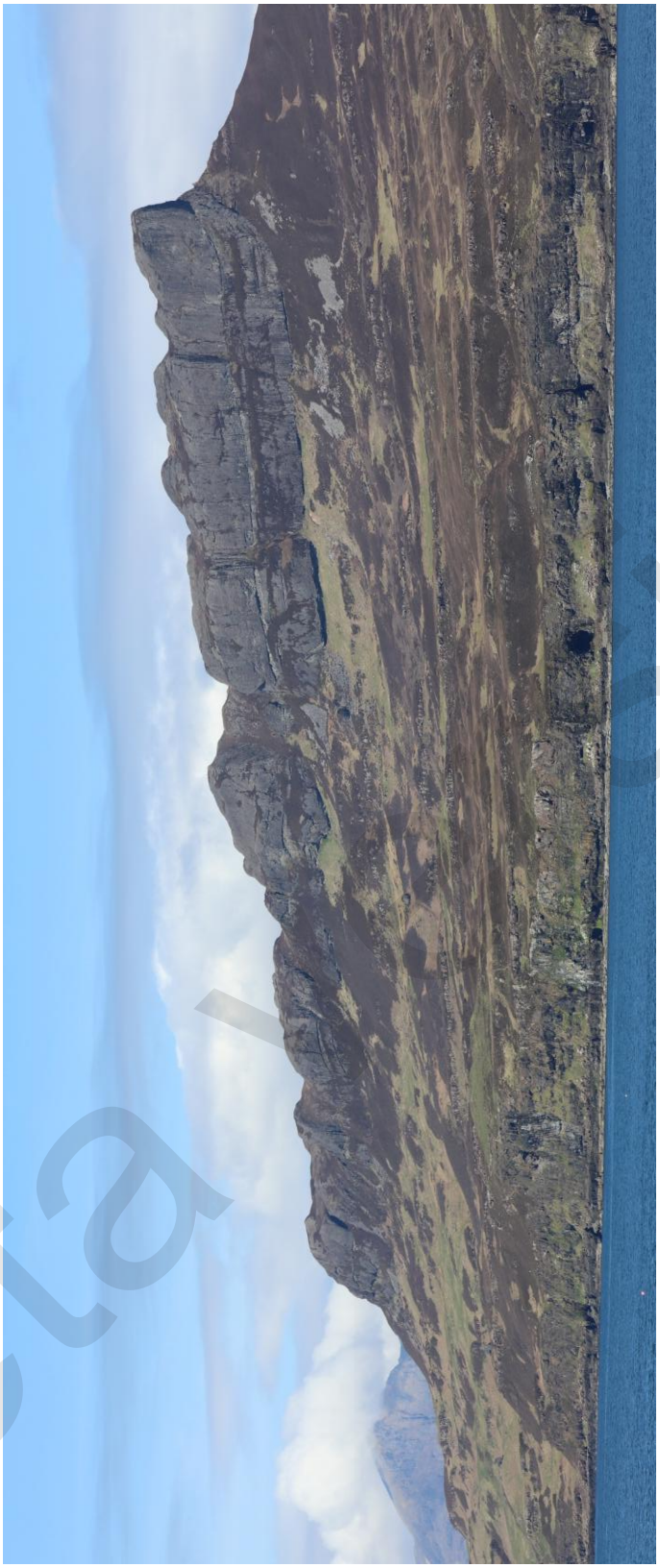


Figure 6-374: Prominent ridge of the Sgùrr of Eigg vitrophyre/ignimbrite, unconformably overlying clastic sedimentary rocks (obvious at eastern end of outcrop), overlying basaltic lavas of the Eigg Lava Formation along the coast at Gruilin Uachdrach, south Eigg.

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Figure 6-375: General view of the volcanic-sedimentary sequence in south Eigg.

Version



Figure 6-376: An Sgùrr, Eigg, viewed towards the NW.

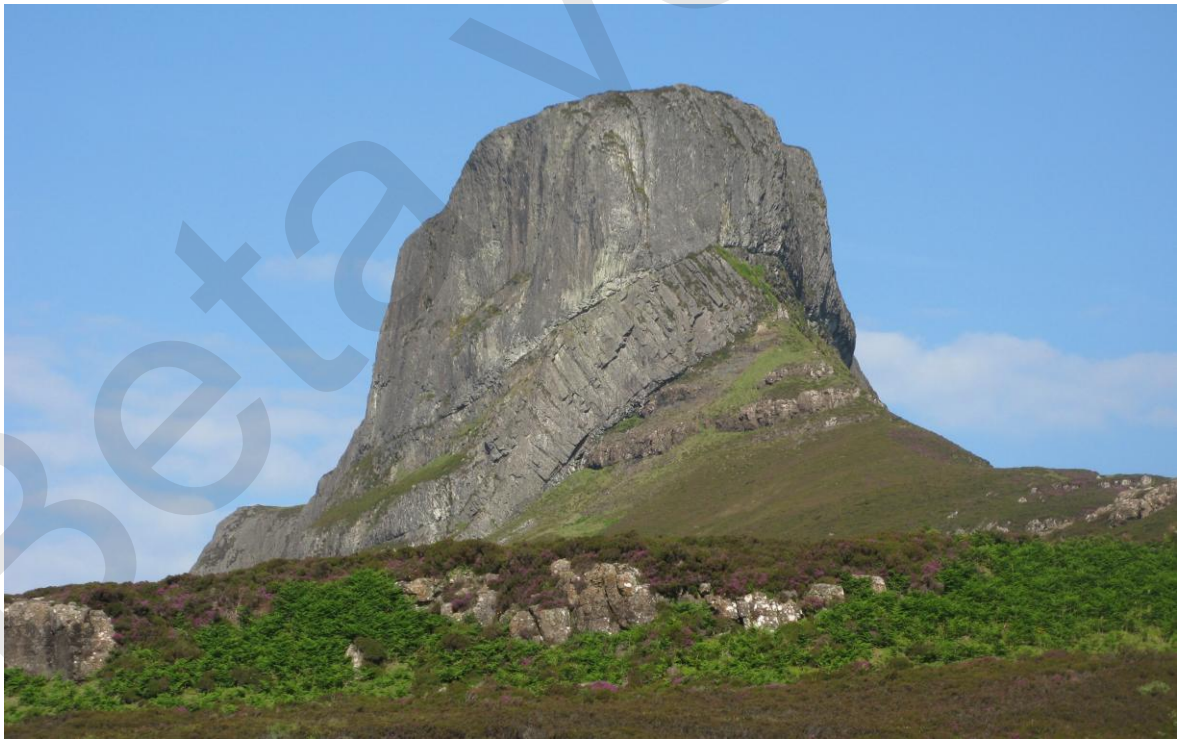


Figure 6-377: An Sgùrr, Eigg, viewed towards the NW.

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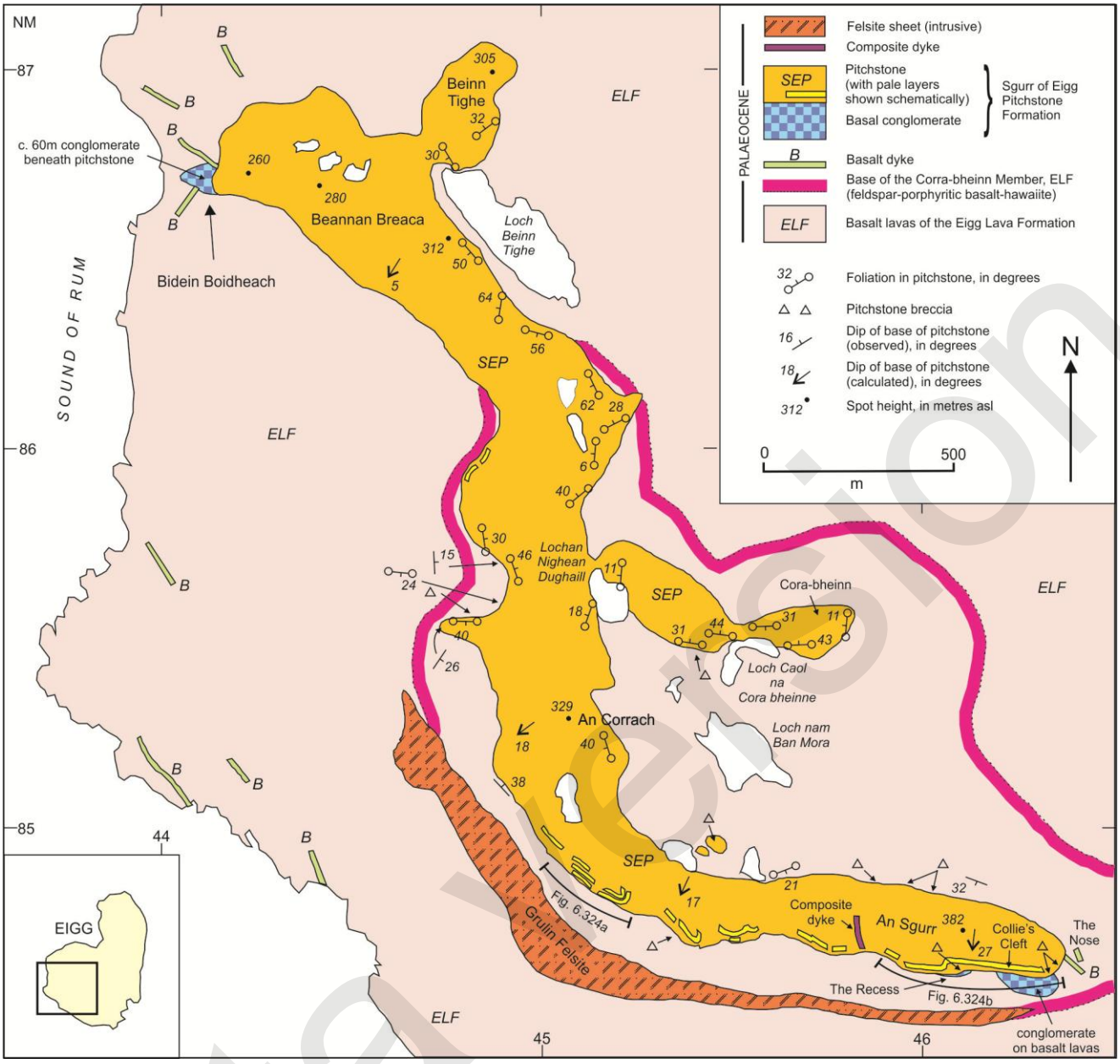


Figure 6-378: Geological map of the Sgùrr of Eigg Formation showing structures within the vitrophyre and the approximate positions of former valleys eroded in the Eigg Lava Formation, which were filled by the vitrophyre, and locally by fluvial boulder conglomerate (after Brown & Bell 2013).

Brown & Bell (2013) interpreted the vitrophyre as a single valley-filling, lava-like, rhyodacite ignimbrite, underlain by a boulder conglomerate (the Basal Conglomerate) (Figure 6-379). Both units are considered to have been deposited in a fluvial channel system and unconformably overlie the main sequence of the Eigg Lava Formation. The toughness and resistance to weathering and erosion of the ignimbrite have led to an inverted topography, whereby this valley-filling unit now forms a prominent ridge. The main outcrop of the ignimbrite in south Eigg forms the sinuous ridge from An Sgùrr in the east, to Beannan Breaca and Bidean Boidheach in the west. A discrete outcrop forms the Oigh-sgeir skerries *ca.* 30 km to the west. The Basal Conglomerate is erratically exposed along the south side of the ignimbrite, at the base of the near-vertical crags forming The Nose, and westward for a short distance; significant but difficult to access exposures occur at Bidean Boidheach. The ignimbrite has an Ar-Ar (isotopic) age of 58.7 Ma (Chapter 5) and is, most likely, one of the youngest igneous units within the Hebridean Igneous Province.

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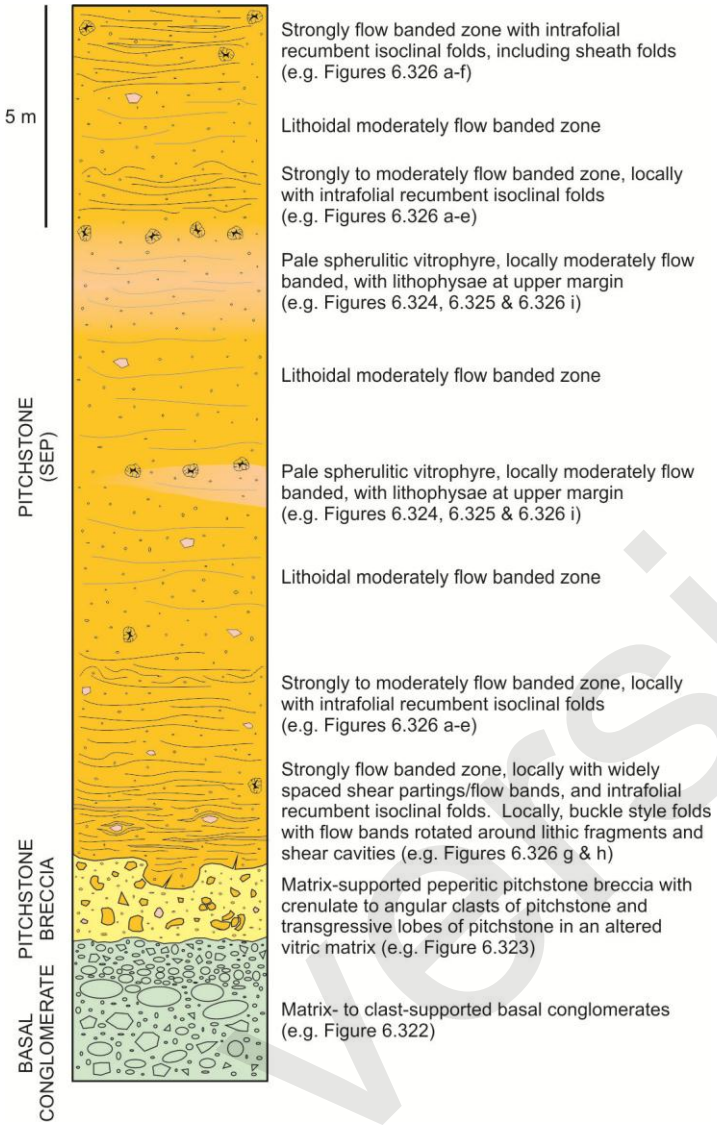


Figure 6-379: Schematic generalized log of part of the Sgurr of Eigg Pitchstone Formation, demonstrating field relationships and the internal textures of the Sgùrr of Eigg vitrophyre (lava-like ignimbrite). Columnar joints are omitted for clarity. Only a representative portion of the vitrophyre is shown: the emplacement units and textures depicted are purely schematic (after Brown & Bell 2013).

6.7.6.2 The Basal Conglomerate

Three masses of conglomerate are exposed at the base of the Sgùrr of Eigg ignimbrite (Figure 6-380). At Bidein Boidheach, the conglomerate is up to 60 m thick and has steep-sided contacts with the underlying basaltic lavas (Figure 6-381). Here, the conglomerates are poorly sorted, weakly bedded and clast- to matrix-supported, with the clasts (sub-rounded to sub-angular; *ca*. 1-2 m across, although more typically 20-50 cm) set in a brown to grey matrix of comminuted sand-size, typically basaltic, material. Locally, clasts are oriented vertically, with long axes orthogonal to the base of the unit. Clasts are typically of Paleocene basalt, red and green sandstone (Late Proterozoic Torridon Group), with rarer examples of red mudstone (Paleocene) and granite (Paleocene?). Discontinuous granule- and pebble-size layers are present, and a weakly developed clast imbrication is preserved, indicating transport from east to west. However, the overall sedimentary motif of these conglomerates is chaotic and poorly sorted.

Similar deposits are exposed *ca*. 10 m below The Nose, east of Collie's Cleft (Figure 6-20). These conglomerates are poorly sorted, with similar clast types and sizes, although discrete and distinctive units

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are recognized. A third outcrop is present in the floor of The Recess; however, the conglomerates here are very poorly exposed. This locality is the site of the Eigg pine (*Pinites eiggensis*), described nearly 200 years ago (Witham 1831; see also Harker 1908) and identified as of Eocene age and contemporaneous with the deposits. Harker (1908) also described fragments of brown wood found with locally abundant pieces of white sandstone.

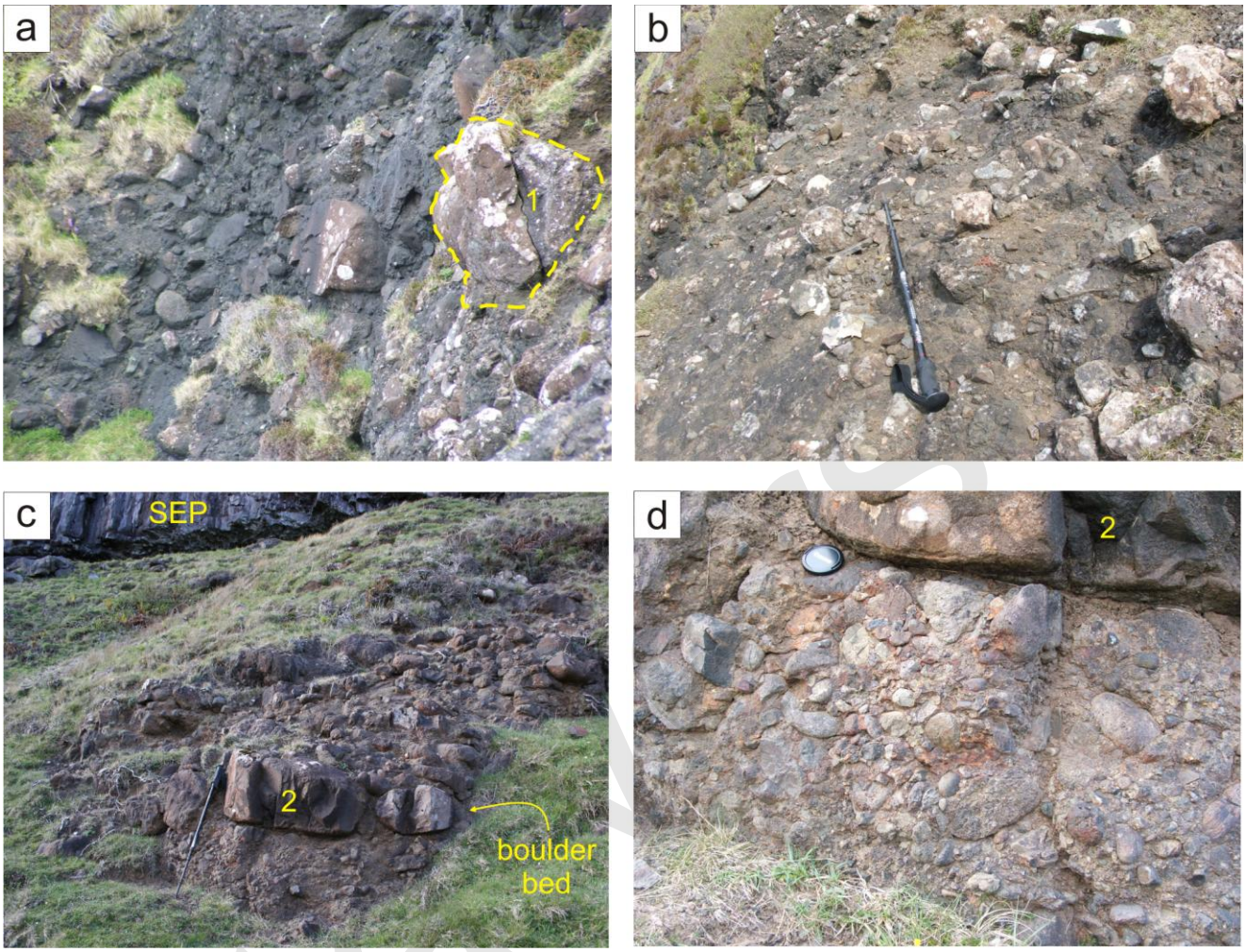


Figure 6-380: Basal conglomerates at Bidein Boidheach (a, b) and east of Collie's Cleft (c, d). (a) clast- to matrix-supported conglomerate with rounded to sub-angular clasts, highlighted boulder (1) is *ca*. 2 m across; (b) matrix-supported conglomerate with sub-rounded to angular clasts, pole *ca*. 1 m long; (c) clast- to matrix supported conglomerate with rounded to sub-angular clasts overlain by boulders (e.g. 2) that form a distinct bed, overlying the Sgùrr of Eigg vitrophyre is indicated, pole *ca*. 1 m long; and, (d) diffusely bedded, clast-supported, poorly sorted conglomerate at base of exposed sequence, Boulder 2 is indicated in (c). Camera lens *ca*. 8 cm across (after Brown & Bell 2013).

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Figure 6-381: Basal conglomerates at Bidein Boidheach, SW Eigg,

6.7.6.3 Basal breccia

Locally, at the base of the ignimbrite is a 1–2 m thick vitrophyre breccia (Figure 6-382). The weathering out of this unit has, in places, given rise to a recess at the foot of the ignimbrite escarpment (Figure 6-384). The breccia is massive, matrix-supported and comprises sub-rounded to angular clasts of crystal-rich ignimbrite/vitrophyre, 1–20 cm across, set in a pale-yellow matrix of sand- to granule-size, thoroughly altered, vitric material. Many clasts display fluidal morphologies with irregular, crenulated margins, and locally jigsaw-fit clasts are preserved. Some clasts display an obvious fluidal fabric or flow banding (0.5–1 cm thick bands). Rare blocks of basalt from the underlying lava field are also present. Locally, the basal contact of the ignimbrite is lobe-like and transgressive within the breccias; the margins of these lobes are typically irregular and crenulated, and contain fractures filled by matrix material.

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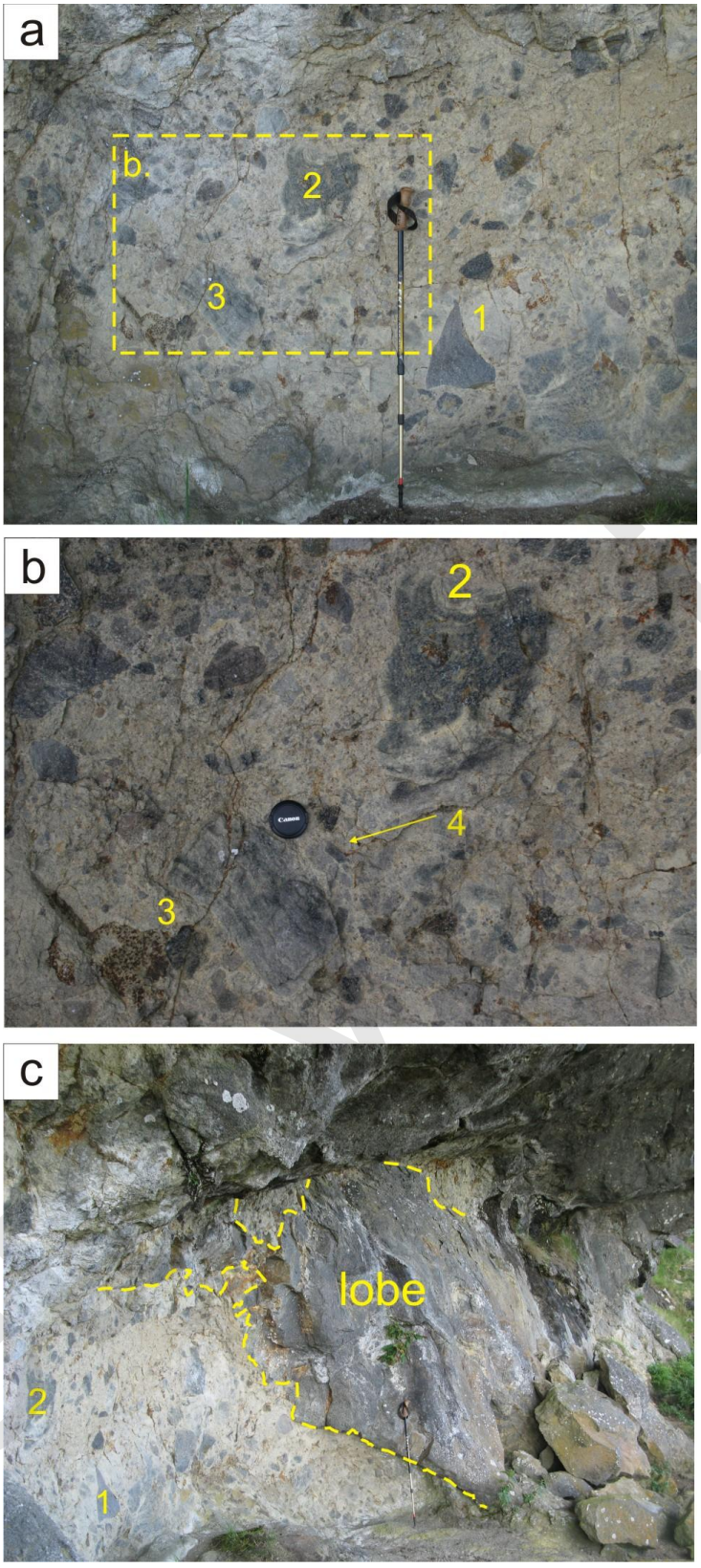


Figure 6-382: Vitrophyre breccia at The Recess, base of Sgùrr of Eigg ignimbrite. (a) angular (1), sub-rounded and fluidal or crenulate (2, 3) clasts of vitrophyre set in a yellow, glassy (devitrified) matrix, pole *ca*. 1 m long, position of (b) is indicated; (b) detail of fluidal or crenulate clasts (2, 3) and area with jigsaw-fit arrangement of clasts (4), lens cap is *ca*. 8 cm across; and, (d) irregular, locally steeply inclined, lobe of vitrophyre invading the breccia, clasts 1 and 2 shown in (a) and (b) are indicated for reference, pole *ca*. 1 m long (after Brown & Bell 2013).

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6.7.6.4 The ignimbrite

The ignimbrite is predominantly lithoidal (microcrystalline or devitrified) and contains crystals up to 1 mm across; locally, it contains vitrophyric (glassy) layers. It is up to 120 m thick and forms a sinuous ridge *ca*. 3.5 km in length, with, where it can be determined, near-vertical sides (Figure 6-384). Much of the near-vertical sides of the ridge is inaccessible, limiting observations to its base, top, and gullies on the southern face (the northern face is poorly exposed). The outcrop is characterized by columnar joints, with columns 0.7–1.5 m across. The orientation of the joints is extremely variable, ranging from predominantly vertical to horizontal, and sweeping through spectacular arcing fans over distances of only a few tens of metres (Figure 6-383; Figure 6-384; Figure 6-385). Many of the columns are also slightly distorted (kinked). At The Nose, the columns are steeply inclined, perpendicular to the palaeo-valley contact.



Figure 6-383: Columnar structure of the Sgùrr of Eigg vitrophyre, An Corrach, south Eigg.

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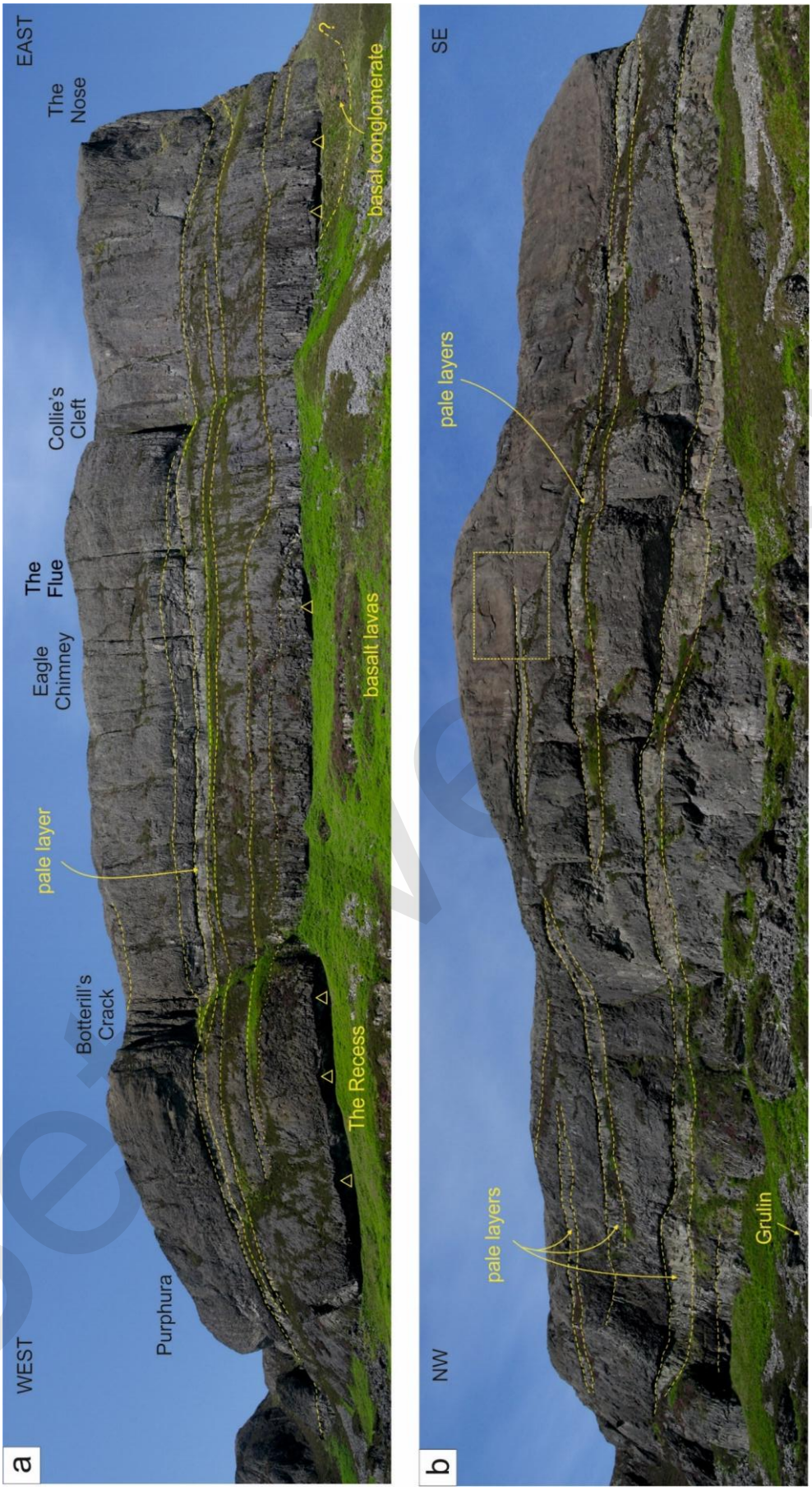


Figure 6-384: Field relationships of the Sgùrr of Eigg vitrophyre. (a) Purphura to The Nose. (b) Grulin. Dashed lines indicate emplacement unit boundaries; dotted lines indicate uncertain boundaries. Triangles indicate exposures of breccia at base of vitrophyre (after Brown & Bell 2013).

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The ignimbrite can be subdivided into discrete units ('emplacement units'), distinguished by: their weathering characteristics; the orientation, spacing and morphology of the columnar joints; and, the presence of sharp, undulating boundaries with marked topographic breaks (Figure 6-384). There are no weathered surfaces, palaeosols, pyroclastic fall deposits or sedimentary rocks between the emplacement units. The emplacement units are typically sub-horizontal and can be traced along strike for tens to hundreds of metres (Figure 6-385). They display complex undulating bounding surfaces and some taper towards their margins, apparently pinching out. Most of the emplacement units have distinctive columnar joint patterns; however, in places, the joints cross emplacement unit boundaries. At The Nose, emplacement units, each with a distinct joint set, merge laterally into one distinct columnar-jointed unit. On the south side of the ridge, distinctive pale layers of ignimbrite, up to *ca*. 5 m thick, are exposed and were originally interpreted as intrusive felsites (Emeleus 1997). Locally, these pale layers merge laterally into the more typical dark emplacement units. Although more altered than the dark emplacement units, the pale layers are typically vitrophyric.

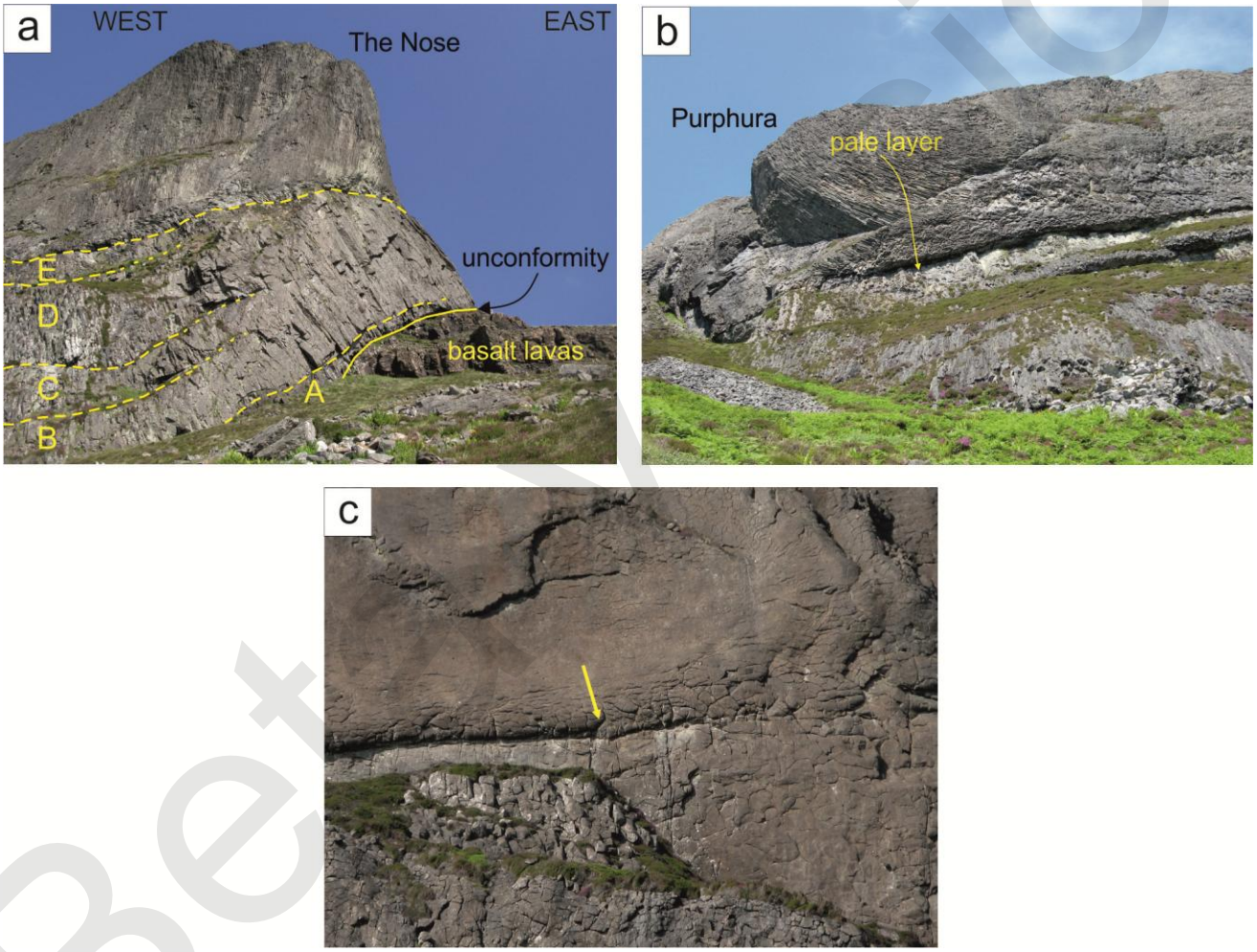


Figure 6-385: (a) Field relationships of the Sgùrr of Eigg vitrophyre at The Nose. The vitrophyre fills a steep-sided palaeo-valley eroded into subjacent basaltic lavas (unconformity). Dashed lines indicate emplacement unit boundaries; dotted lines indicate uncertain boundaries. The amalgamation of cooling joints within emplacement units A–E into a single cooling unit towards The Nose should be noted; (b) detail of emplacement unit at Purphura showing spectacular arcing columnar joints overlying a pale layer; and, (c) detail of a pale layer in the Grulin section. Arrow indicates where a pale layer merges laterally into a more typical dark emplacement unit (after Brown & Bell 2013).

At Bidein Boidheach, Emeleus (1997) identified a 3 m thick zone of welded tuff, including a 1.5 m thick zone of fissile, sparsely porphyritic, welded vitric tuff, at the base of the ignimbrite. This zone is

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characterized by a well-developed fabric, or banding, parallel to the base of the ignimbrite, and was interpreted as an initial ash-flow tuff deposited prior to the eruption of 'pitchstone' lavas. However, a similarly oriented fabric occurs throughout the whole outcrop (Figure 6-386), including the pale layers. The fabric is most conspicuous towards the base and top of the ignimbrite; however, examination of much of the unit is restricted by its sheer, near-vertical cliff faces. The fabric is base-parallel and comprises relatively planar, discontinuous, subparallel lenses, bands or shear partings of compositionally distinct dark or light material, typically 0.1-3 cm thick and up to several metres in length, set in a paler or darker matrix (Figure 6-386 a-f). The length-to-thickness ratio of the lenses, bands and shear partings is typically >>10:1. The fabric locally comprises macroscale intrafolial recumbent isoclinal folds, some of which display eye structures that may represent sheath folds (Figure 6-386 g&h). No measurable elongation lineations have been observed, although the eye structures are oriented NW–SE, approximately along the palaeo-valley axis. Locally, and typically towards the base of the ignimbrite, the planar fabric is more complexly deformed and both open and curvilinear folds, and refolded isoclinal folds with shear cavities at their hinges, are present (Figure 6-386 h). Similar fabrics are locally present in the pale layers.

Small fragments of basalt (2–10 cm; of Eigg Lava Field type) are also present throughout the ignimbrite and decrease in abundance, up-section. At the base of the ignimbrite, the fabric is deformed and flattened around such lithic fragments. No distinct lithic layers have been identified.

Lithophysae, cavities with hydrothermal mineral infills, occur throughout the ignimbrite but are most conspicuous on the flat-lying slabs towards the top of the outcrop. They appear to define discrete zones and typically occur at the upper margin of emplacement units and, in particular, above the pale layers (Figure 6-386). Single lithophysae are up to 20 cm across and are filled or lined with pale brown chalcedony, white zeolites and colourless prismatic quartz with pyramidal terminations (Figure 6-386 i). Alteration haloes, typically 10 cm across, are common.

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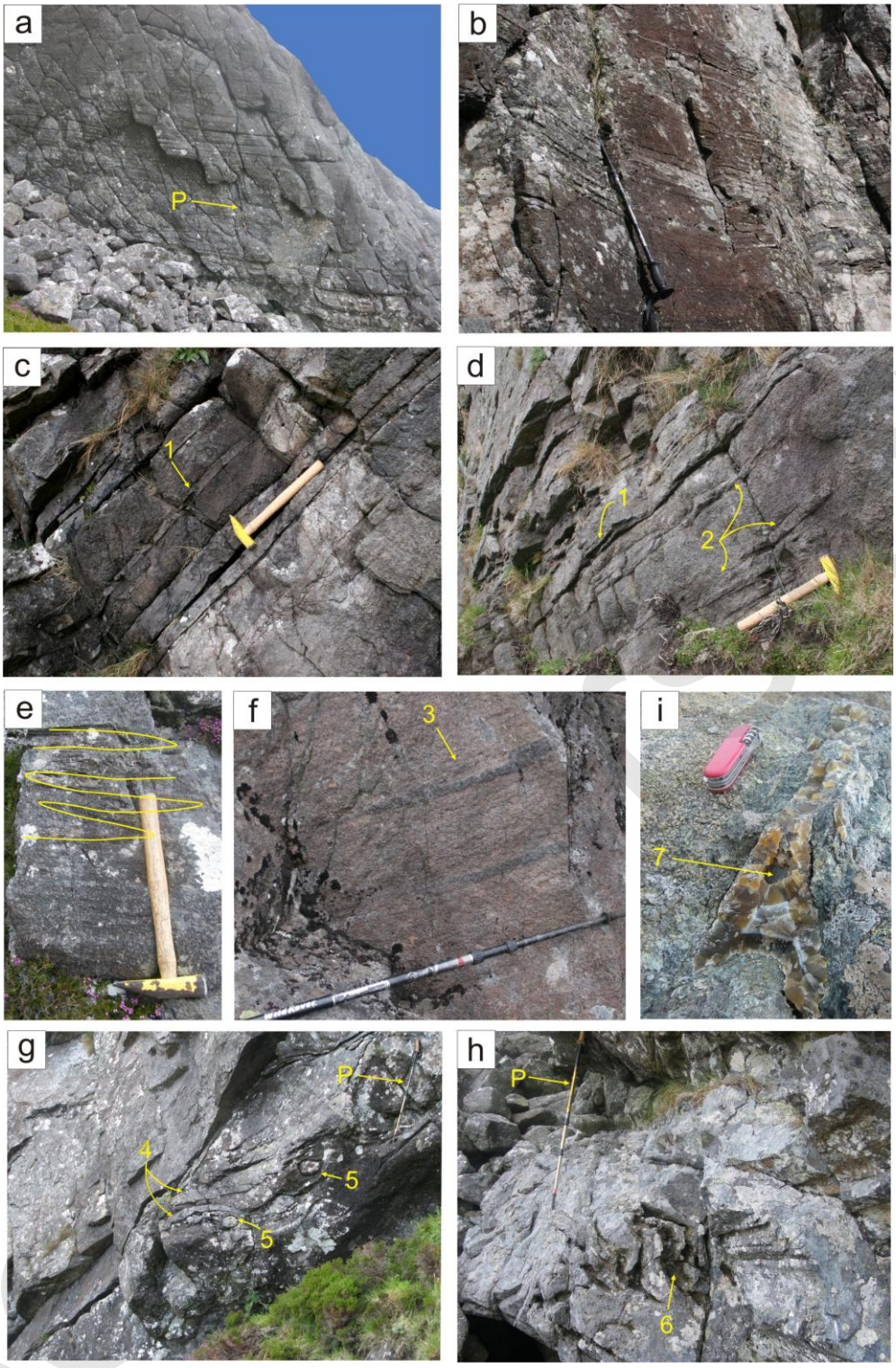


Figure 6-386: Field characteristics of the Sgùrr of Eigg vitrophyre, pole (P) *ca*. 1 m long, hammer *ca*. 30 cm long, knife *ca*. 10 cm long. (a) Flow fabric (flow banding), south side of An Sgùrr; (b) flow fabric (flow banding) at Bidein Boidheach; (c) flow fabric defined by prominent compositional banding or shear partings (1), at The Nose; (d) flow fabric defined by prominent compositional banding or shear partings (1), some of which display recumbent isoclinal folds (2), at The Nose; (e) intrafolial recumbent isoclinal to tight folds (refolded?), south side of An Sgùrr; (f) intrafolial recumbent isoclinal fold (possible sheath fold?) (3), near the summit of An Sgùrr; (g) open to curvilinear folds (4) near the base of the vitrophyre at The Nose; (h) buckle type folds with shear cavities (6), south side of An Sgùrr; (i) chalcedony-filled lithophysae (7), west of the summit of An Sgùrr, arrowhead indicates central cavity (after Brown & Bell 2013).

6.7.6.5 Emplacement and rheomorphic deformation of the ignimbrite

Owing to the ubiquitous presence of rheomorphic structures (i.e. the presence of flow banding) and the absence of pumiceous material, Brown & Bell (2013) interpreted the vitrophyre that forms the sinuous ridge of the Sgùrr of Eigg as a high-grade ignimbrite formed during a so called 'boil-over eruption', whereby low pyroclastic fountaining produced a quasi-steady pyroclastic density current. However, the presence of vitroclastic textures ranging from eutaxitic to parataxitic indicates periodic waxing and waning of current competence and variations in eruption temperature and welding. Allwright (1980) and Emeleus (1997) demonstrated that the ignimbrite fills a palaeo-valley in the Eigg Lava Field, and this is consistent with depositional models of other high-grade ignimbrites that fill pre-existing topographic lows.

Brown & Bell (2013) interpreted the ignimbrite as the product of sustained deposition during a single eruption, with the emplacement units reflecting discrete depositional events (Figure 6-387). The absence of weathered surfaces, palaeosols, pyroclastic fall deposits or sedimentary rocks at emplacement unit boundaries strongly suggest deposition from a single eruption. The emplacement units represent distinct depositional packages that may reflect changes in flow steadiness, or, more likely, several rapidly emplaced ignimbrites, which welded, cooled and devitrified as a simple, essentially single, cooling unit. Some emplacement units have their own distinctive joint patterns, which indicate that they were able to part-cool individually and were probably emplaced over relatively colder, earlier-deposited units. However, many joints cross emplacement unit boundaries, and/or emplacement units 'amalgamate' into simpler elements, thus demonstrating that these packages essentially behaved as one cooling unit. Together, these relationships suggest that hiatuses between the deposition of emplacement units were relatively short, and that the ignimbrite formed during a sustained, but punctuated, eruption (Figure 6-387).

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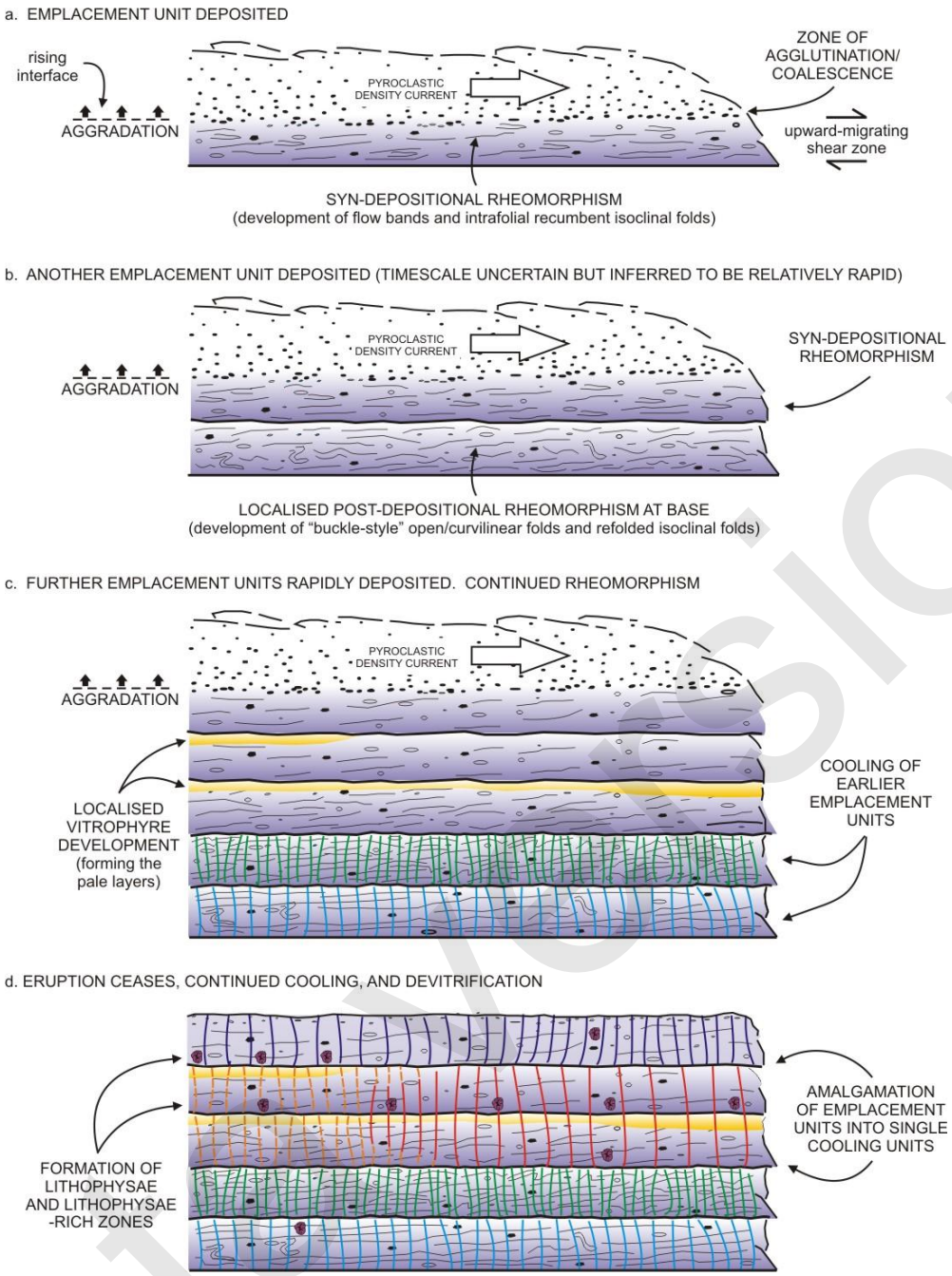


Figure 6-387: Schematic model of deposition of the Sgùrr of Eigg vitrophyre/ignimbrite. Not to scale. Rheomorphic features and lithophysae are exaggerated for clarity. The emplacement units depicted are purely schematic and are not representative of actual emplacement units (after Brown & Bell 2013).

The pale layers in the ignimbrite were interpreted by Emeleus (1997) as intrusive felsites. However, the pale layers are integral parts of the ignimbrite because they exhibit the same texture as observed in the more typical dark emplacement units, and in places they merge laterally into the dark emplacement units (Figure 6-387) and therefore cannot have been formed by intrusion into the ignimbrite. The pale layers do, in places, however, have a distinct microscopic texture from that of the dark emplacement units. Brown & Bell (2013) interpreted these sub-spherical structures as spherulites that formed during devitrification of original glass. These originally vitric layers are interpreted as basal and upper vitrophyres of the dark emplacement units, which locally thin to conformable horizons, no longer recognizable. The presence of lithophysae and, in particular, lithophysae-rich zones towards the top of emplacement units and above the pale vitrophyres, is indicative of rapid cooling and volatile degassing between the deposition of

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emplacement units. During degassing, vapour-phase alteration could also have caused chemical and thermal modification of the emplacement units.

The pervasive base-parallel flow banding and intrafolial recumbent isoclinal folds (and possible sheath folds) in the ignimbrite (Figure 6-387) indicate that rheomorphism occurred throughout its deposition. As hot particles were deposited, they rapidly agglutinated and coalesced, and underwent non-coaxial shear in a sub-horizontal ductile shear zone close to the depositional boundary layer (i.e. just below the pyroclastic density current-deposit interface). The shear zone produced and deformed the rheomorphic fabric and migrated upward with the rising depositional boundary layer during aggradation, such that the entire ignimbrite was subject to noncoaxial deformation (in a lava, such deformation would be restricted to a basal shear zone). Post-depositional rheomorphism typically produces pervasive buckle-style folds that refold earlier isoclinal, recumbent folds. Such features are locally present at the base of the ignimbrite (Figure 6-387) and suggest some minor post-depositional rheomorphism owing to spreading or downslope sliding of the hot deposit. Extensive post-depositional rheomorphism, as seen in other lava-like ignimbrites, was possibly limited by the confines of the palaeo-valley.

6.7.6.6 Oigh-sgeir

Oigh-sgeir is a group of skerries *ca.* 9 km SW of Canna. The islets are made of columnar-jointed vitrophyre, near identical to that which forms the Sgùrr of Eigg (Figure 6-388; Figure 6-389). They were described by Sir Archibald Geikie (1897, also by Harker 1908), who noted devitrification of the dark, resinous, porphyritic 'pitchstone'. Structural, petrographic and compositional similarities are certainly impressive. If the ignimbrite originated as a silicic ash flow, there would be little difficulty in accepting their consanguinity, have traversed the intervening *ca.* 30 km in a very short time, possibly a few hours.



Figure 6-388 : Oigh-sgeir, SW of Canna, composed of the same vitrophyre/ignimbrite unit that forms the Sgùrr of Eigg.



Figure 6-389: Columnar-jointed vitrophyre, Oigh-sgeir.

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6.8 The Mull Lava Field

6.8.1 Introduction

The Mull Lava Field (or Group) crops out throughout north and west Mull, together with the coastal parts of south Mull (around the margin of the younger Mull Central Complex, Chapter 9) and the various offshore islands to the west, including Ulva, Gometra, the Treshnish Islands and Staffa. The successions of flat-lying lavas form substantial mountains, such as Ben More, and commonly develop strong trap featuring. The lavas on Morvern, Scottish Mainland, east of Mull, also belong to the Mull Lava Group, as do the lavas east of Ben Hiant, Ardnamurchan, and most likely also the isolated outcrops on the south coast of Ardnamurchan. Offshore lavas, which extend beneath the Sea of the Hebrides to the Skerryvore Fault, are possibly part of the Mull Lava Group. These lavas are most likely contemporaneous with those of the Eigg Lava Formation, which they join in a northern, submarine extension (Fyfe *et al.* 1993; Chapter 5).

There has been no detailed regional mapping of the Mull Lava Field since the time of the original survey (Bailey *et al.* 1924). This account, therefore, focuses on a more recent examination of the sequences in SW Mull and adjacent small islands by Williamson & Bell (2012), the so-called Staffa (Lava) formation, plus sporadic observations by the authors and others over the rest of Mull, Morvern and Ardnamurchan, and relies to some extent on the synthesis of Richey (1961).The lava stratigraphy has been rationalised here, in keeping with that used for the other lava sequences (Figure 6-390).

The remains of the Mull Lava Field, as presently exposed, cover an area of *ca.* 840 km^2 on Mull and Morvern. The total preserved thickness of lavas on Mull is estimated to be *ca.*1800 m (including a speculative estimate of *ca.* 900 m of olivine-poor tholeiitic basalt lavas now largely within the Mull Central Complex). On Morvern, the sequence is *ca.* 460 m thick, although the lowest lavas thin towards the north (Bailey et al. 1924) and are overstepped by subsequent lavas. A thin, laterally continuous sequence of Upper Cretaceous rocks underlies the lavas of Morvern except in the extreme east and NE of the lava field, where the lavas rest directly on pre-Cretaceous rocks (Triassic sandstones, and gneisses of the Moine Supergroup). The marginal portion of the lava field had therefore erupted onto, and possibly terminated against, a land surface with a significant topographical relief. The NW-trending Assapol Fault, in SW Mull, defines the present-day SW margin of the lava field.

The volcanic succession on Mull (Figure 6-390; Figure 6-391) is divided into the Staffa Lava Formation at the base, overlain by the Mull Plateau Lava Formation that consists of the Ben More Main Member and the overlying Ben More Pale Member; these were formerly named, respectively as the Staffa, Main and Pale ‘suites’, of the Plateau Group (e.g. Bailey *et al.* 1924; Richey 1961). As noted above, the Mull Central Lava Formation crops out principally within the Mull Central Complex and consists of olivine-poor tholeiitic basalt lavas.

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Subdivisions	Description / Lithology
Central Mull Formation / sub-Group (youngest)	Tholeiitic basalt lavas (includes pillow lavas in the Mull Central Complex)
Coire Gorme Formation	Basaltic lavas
Mull Plateau Lava Formation ('Plateau Formation')	
Ben More Pale Member	Sheet-form and restricted tabular form differentiates (mugearites; benmoreites; trachytes)
Undivided	Thin sheet-form alkali- and alkali-olivine basalt lavas & differentiates; sedimentary interbeds are relatively rare; palaeosols relatively common
Staffa Lava Formation (oldest) Genetic Sequences (GS) A1 - A7	Thick 'tholeiitic' basaltic lavas, many with spectacular columnar joint facies and associated flow- and hyaloclastite-breccia facies; common sheet flows covering significant areas; abrupt thickness changes attributed to ponding; rare interbedded alkali-olivine basalt flows low in sequence; numerous and varied interbedded sedimentary (siliciclastic & volcaniclastic) units; relatively rare palaeosols (compared to the Plateau Formation)

Thickness estimates:
Total Succession: *c.* 2000m (Bailey *et al.* 1924); *c.* 2200m (Walker 1970; Kerr 1997)
Central Mull Formation / sub-Group: *c.* 900m (Skelhorn *et al.* 1969)
Plateau Formation: *c.* 1800m (Emeleus & Bell 2005); *c.* 730m (Kerr *et al.*1999); Coire Gorm Formation: *c.* 250m (Kerr 1995a)
Staffa Lava Formation: *c.* 300m (this study)

Abbreviations used in main text:
NPCMT: Non-porphyritic Central Magma-Type; PMT: Plateau Magma-Type; SMT: Staffa Magma-Type;
SMsT: Staffa Magma sub-Type; CMTMT: Central Mull Tholeiite Magma-Type; CGMT: Coire Gorme Magma-Type

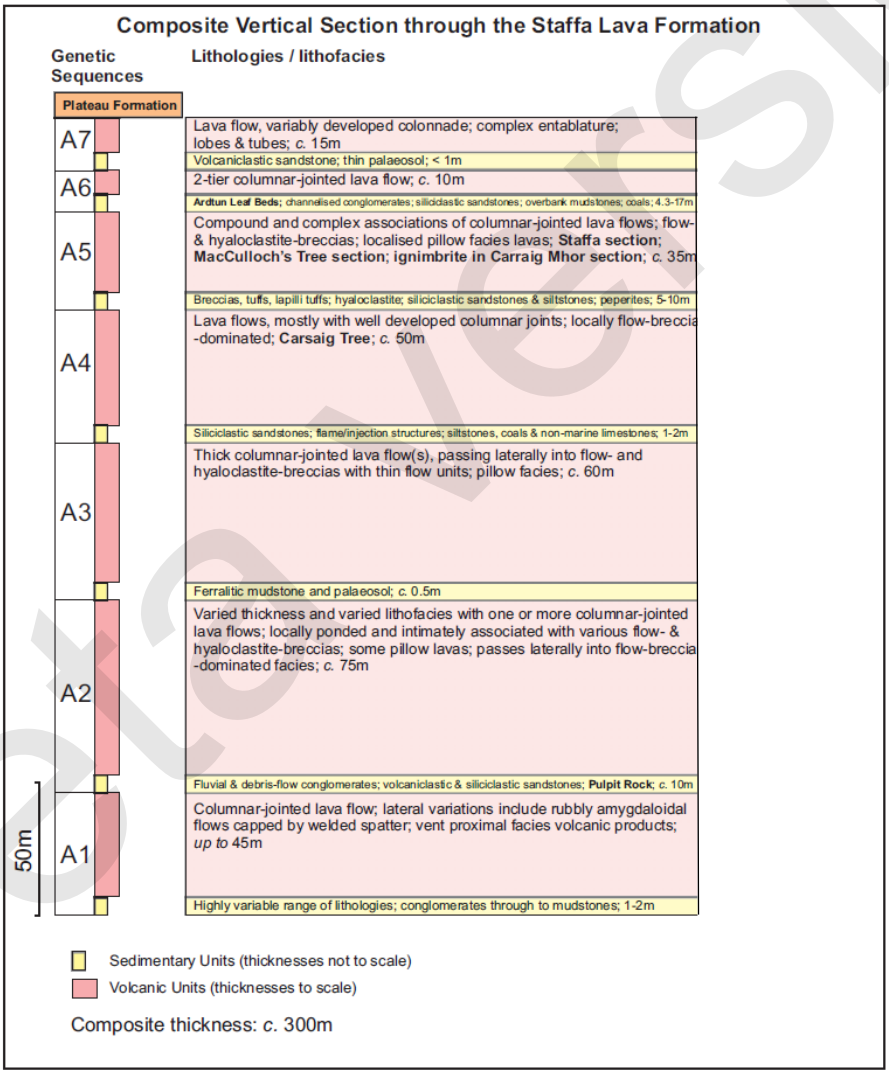


Figure 6-390: Stratigraphical subdivisions of the Paleocene Mull Lava Field and the Staffa Lava Formation (from Williamson & Bell 2012).

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The sequence built up by the effusion of lavas, predominantly from NW-SE-trending fissures now represented by the Mull Main Dyke Swarm (Chapter 7). Pauses in the volcanic activity were more common during eruption of the lower part of the succession, marked by the development of laterally discontinuous sequences of conglomerates, sandstones, siltstones and coals. However, unlike the lava piles elsewhere in the Hebridean Igneous Province, the current subdivisions of the Mull lavas are based on lithological changes in the lavas and do not always depend on the presence of interflow sedimentary sequences.

Zeolite minerals are common throughout the lavas. These have been shown to have a depth-related distribution (Walker 1971) (Figure 6-392) similar to the zonal distributions found in Icelandic lavas. The highest zone is characterised by laumontite and overlies a mesolite zone. Based on comparisons with Icelandic zones, it is estimated that the lava sequence in the vicinity of Ben More was originally over 2,200 m thick, of which *ca.* 1000 m is preserved. A distinct zone characterised by carbonate minerals occurs in the lavas near Tobermory and in NW Morvern, becoming wider northwards towards Ben Hiant on Ardnamurchan. It has been tentatively suggested that the carbonate may have been deposited by circulating heated waters from the Ardnamurchan Central Complex (Walker 1971). The Mull Central Complex is surrounded by a zone of pneumatolysis, which is superimposed on the depth-related zeolite zones (Figure 6-392).

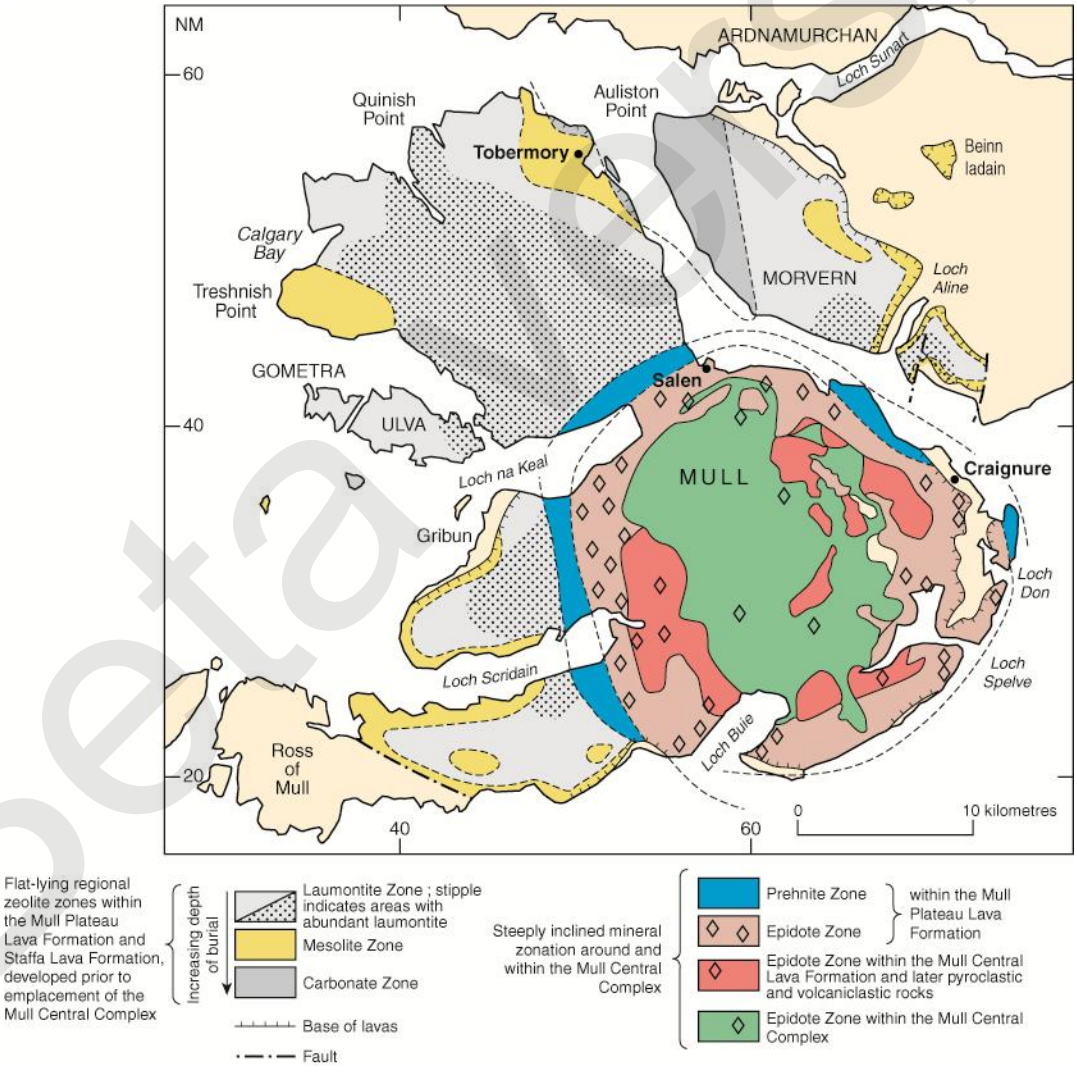


Figure 6-391: Lavas on Mull and Morvern: distribution of hydrothermal mineral zones (after Walker 1971).

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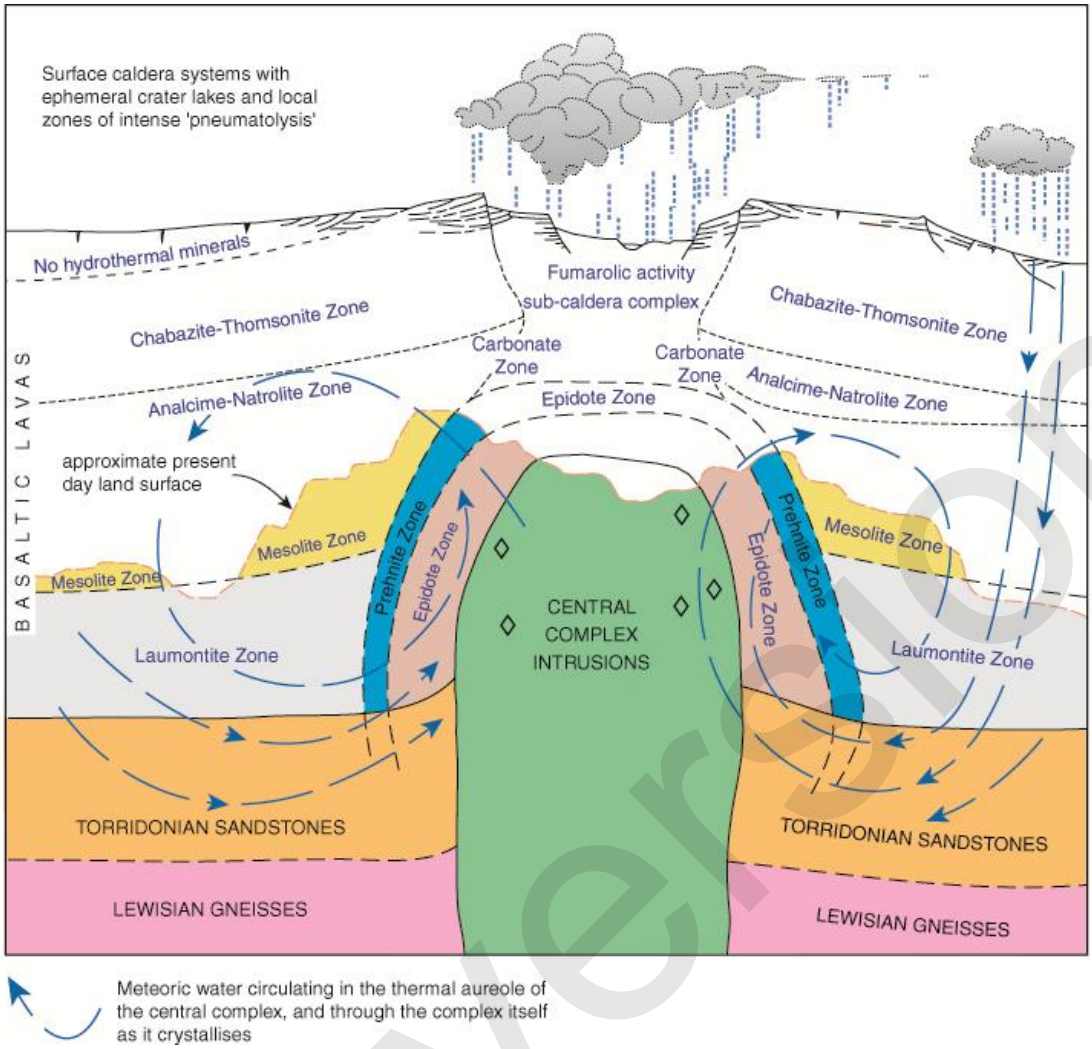


Figure 6-392: Hydrothermal circulation in and around the Mull Central Complex (after Walker 1971; Taylor & Forester 1971; and, Bell & Williamson 2002).

6.8.2 Staffa Lava Formation

6.8.2.1 Introduction

The Staffa Lava Formation is restricted to the SW portion of Mull, together with the offshore islands to the west, including Staffa and Ulva (Williamson & Bell 2012) (Figure 6-393; Figure 6-394; Figure 6-395; Figure 6-396; Figure 6-397; Figure 6-398; Figure 6-399). The basal part of the volcanic sequence on Mull, and locally on Ardnamurchan, is marked by the development of a laterally persistent mudstone, the Gribun Mudstone Member, commonly less than 1 m thick, but thicker at several localities. In Morvern it is referred to locally as the Beinn Iadain Mudstone Formation. Near Feorlin Cottage at Carsaig, Mull, the mudstone occurs within cavities that developed on the surface of chalk (of possible Turonian age) (Chapter 3). On the Croggan peninsula, south of Loch Buie, at An Garradh, the member consists of *ca*. 6 m of buff-coloured calcareous mudstone (marl) and is thought to represent a more aluminous equivalent. These features, together with certain petrographical characteristics (for example, the presence of quartz grains), suggest that the mudstone is the product of extreme lateritic weathering of a basaltic ash, which was deposited prior to the effusion of the overlying lavas. The quartz grains were possibly derived from Cenomanian sandstones and introduced either by alluvial or aeolian processes.

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Figure 6-393: Staffa Lava Formation on south Brolass coast, Ross of Mull, SW Mull, westwards towards Malcolm's Point from Carsaig.



Figure 6-394: Staffa Lava Formation on south Brolass coast, Ross of Mull, SW Mull, eastwards towards the Pulpit Rock and overlying volcanic sequence.

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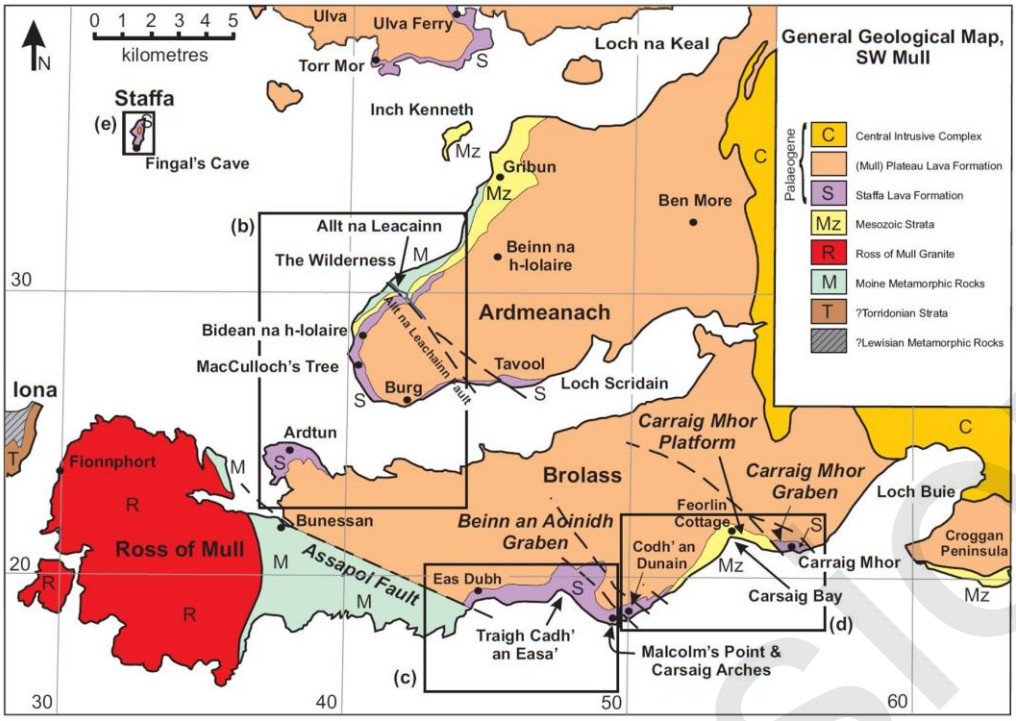


Figure 6-395: Simplified geological map with place names for SW Mull (from Williamson & Bell 2012).

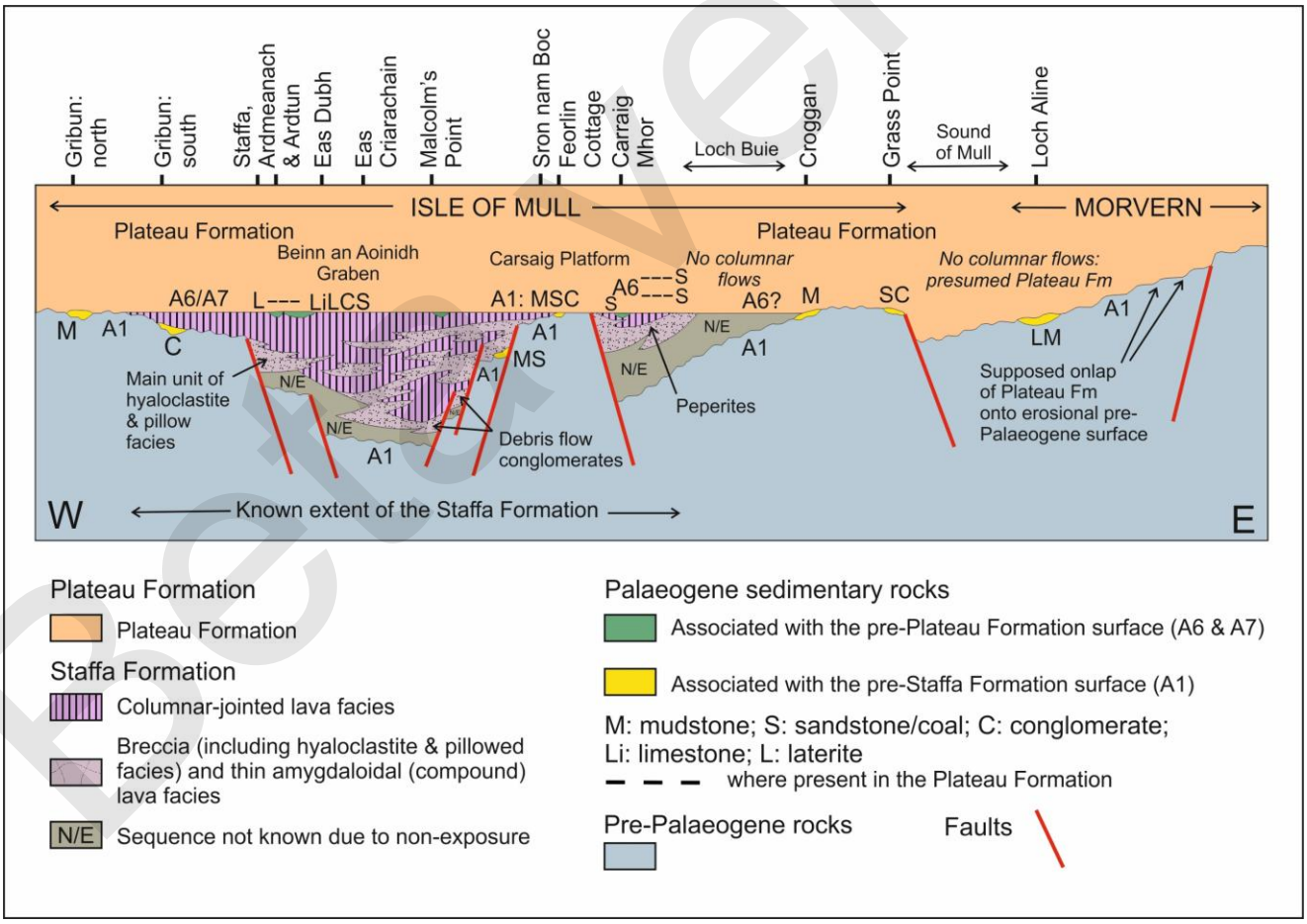


Figure 6-396: Generalised schematic cross-section of the lava succession in SW Mull, illustrating relationships between volcanic facies and intercalated sedimentary rocks of the Staffa Lava Formation, to 'basement' structures and to the succeeding Mull Plateau Lava Formation (from Williamson & Bell 2012).

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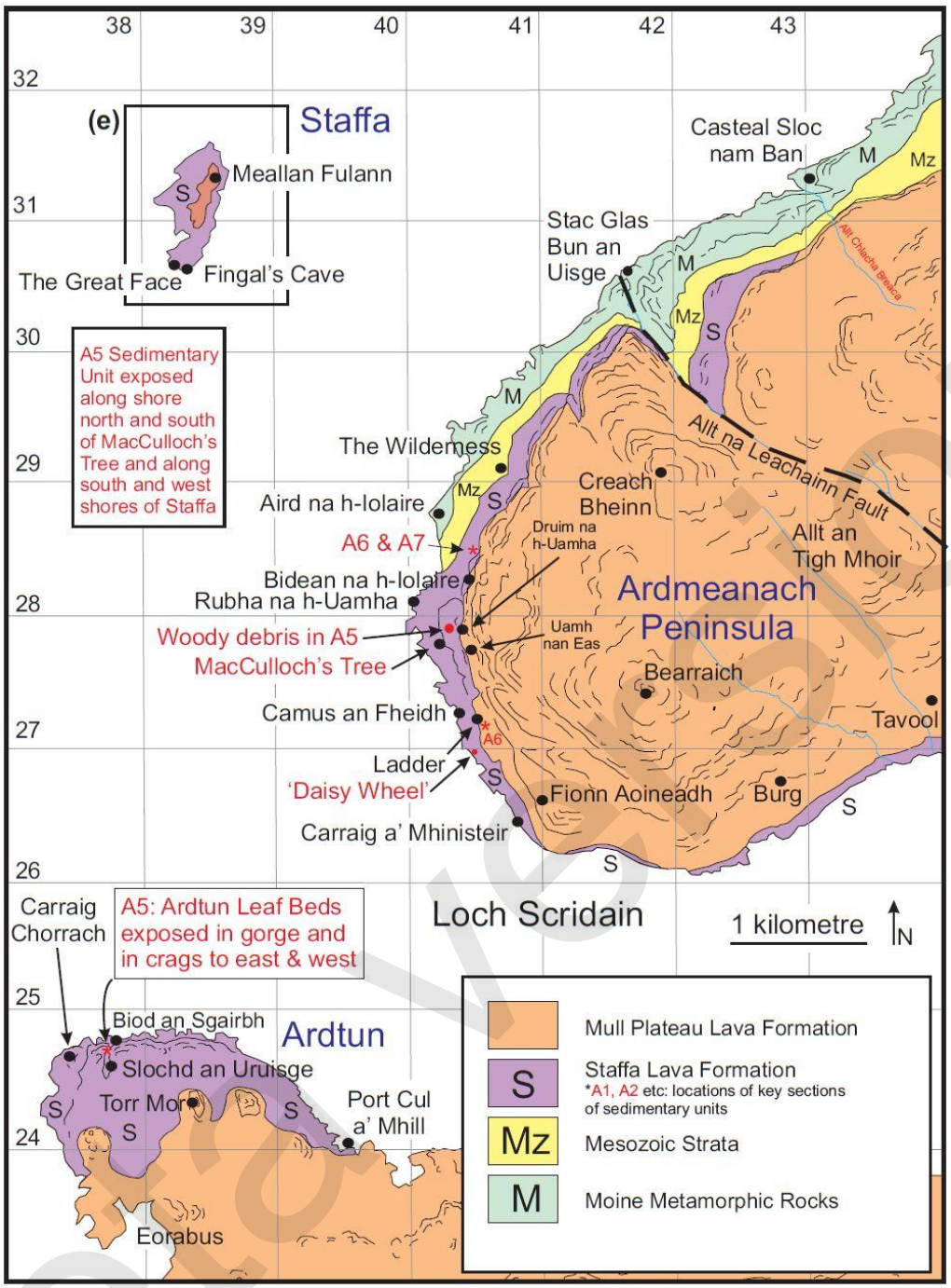
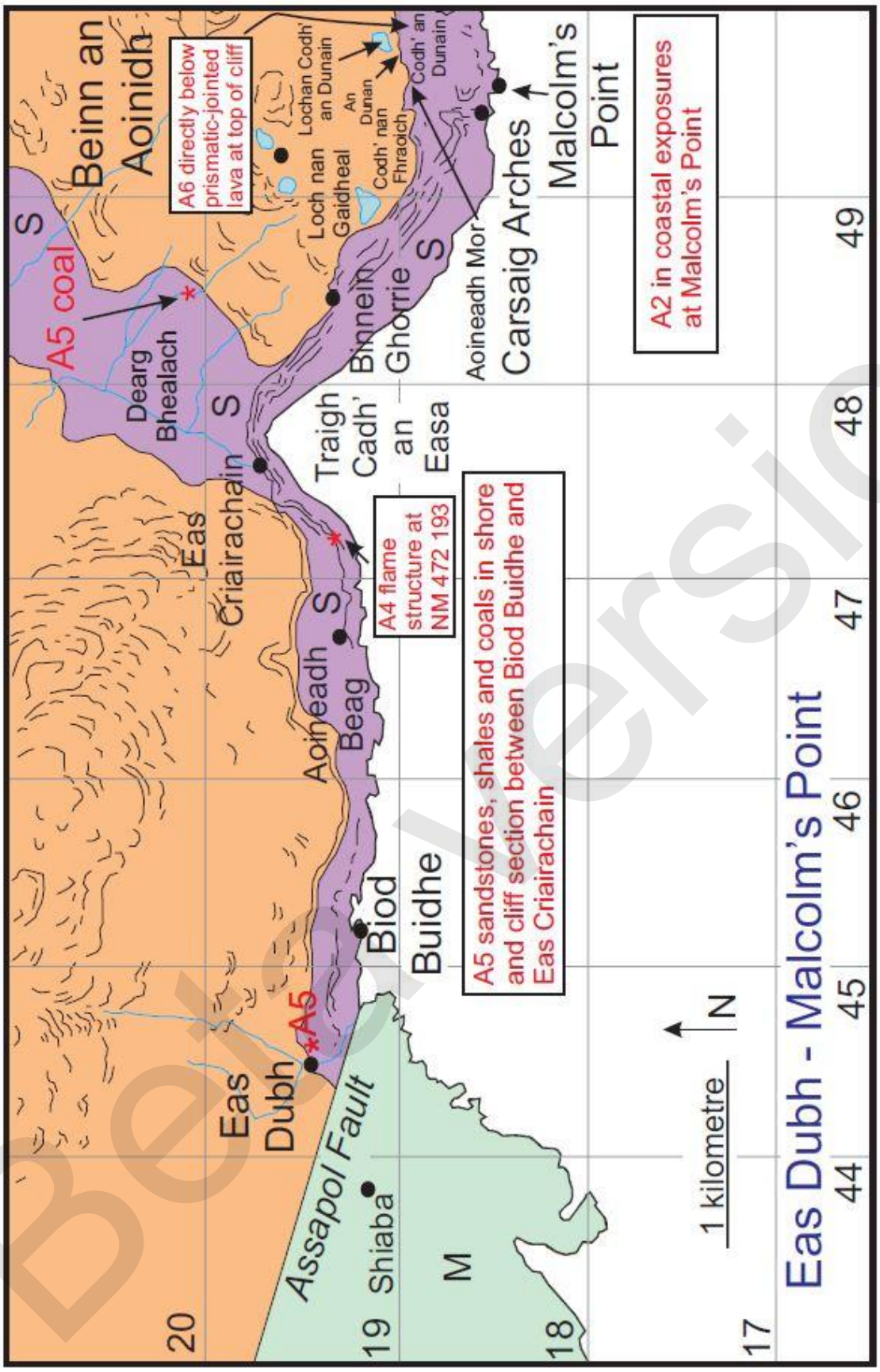


Figure 6-397: Simplified geological map with place names for the Ardmeanach - Ardtun area (from Williamson & Bell 2012).

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Figure 6-398: Simplified geological map with place names for Eas Dubh to Malcolm's Point on the south coast of the Ross of Mull (from Williamson & Bell 2012).

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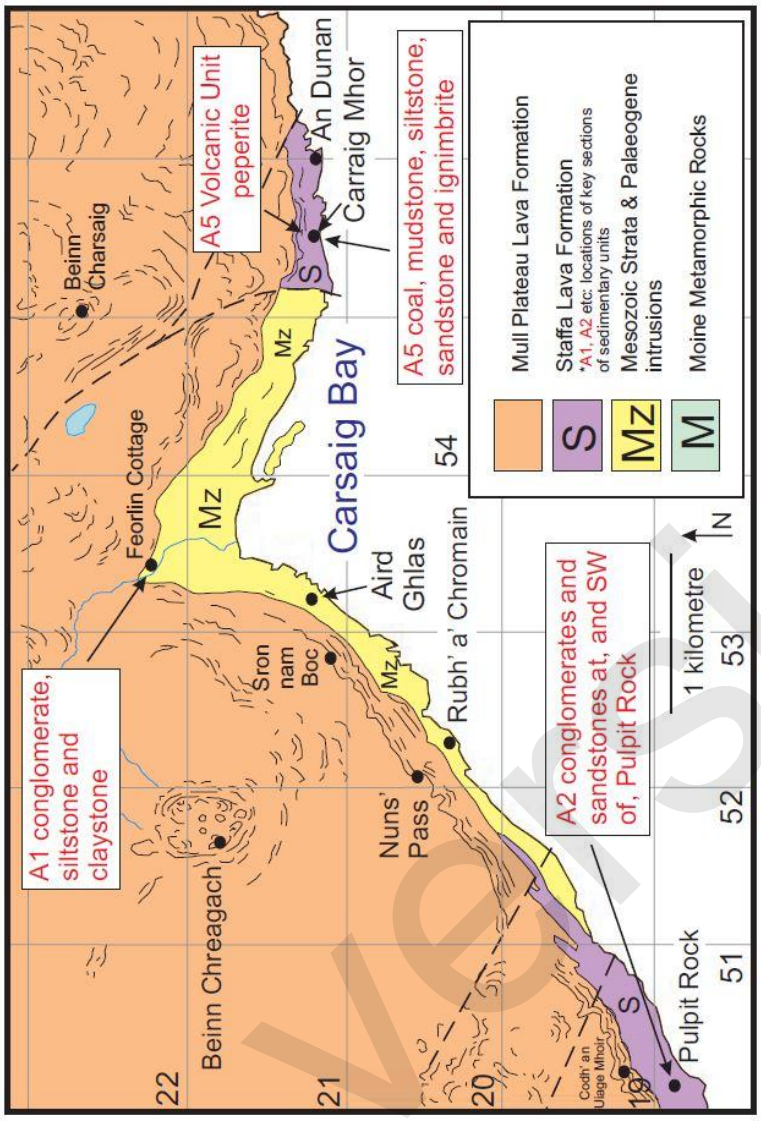


Figure 6-399: Simplified geological map with place names for Carsaig Bay on the south coast of the Ross of Mull (from Williamson & Bell 2012).

The Staffa Lava Formation comprises the sequence of volcanic and sedimentary rocks lying between the sub-Paleocene unconformity and the base of the Mull Plateau Lava Formation (see below): both boundaries are diachronous. The upper boundary can be placed above either the uppermost lava of recognizable Staffa Lava Formation-type or the uppermost sedimentary unit recognized within the Formation. Above this level there is a significant change in the nature and make-up of the MLF (Figure 6-396). The presence of well developed, two-tiered (colonnade-entablature) or, less commonly, multi-tiered, columnar-jointed lavas is taken as diagnostic, at least as far as field-based criteria permits, and in all known cases such lavas are attributable to the Formation.

Lavas with well-developed columnar joints have undergone regular, uninterrupted (i.e. static) and insulated basal cooling, either flowing over a wet substrate or into a shallow body of water, together with more rapid and uncontrolled cooling caused by the ingress of water through the upper surface of the lava. The long-axis orientation of columns (developed perpendicular to the local cooling surface), and the gross lenticular geometries of such lavas, as well as abnormally thick accumulations of, and association with, hyaloclastite breccias, collectively indicate ponding and commonly the impounding of palaeo-drainage systems.

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The development of columnar joints is, therefore, environmentally dependent, but its absence cannot be considered diagnostic. Thin, massive to rubbly and amygdaloidal lavas locally form subordinate parts of sequences and, where in close association with lava breccia, may be the dominant facies (Figure 6-396). It is not always obvious whether these are lateral variants of the columnar-jointed (tholeiitic) basalt lavas or whether they are distinct alkali-olivine basalt lavas. For example, Kerr (1995a) reported the presence of several non-columnar, transitional (tholeiitic-alkalic) lavas close to the base of the sequence of Mull Plateau Lava Formation type flows. Such inter-stratification of disparate lava types was previously difficult to explain. However, Kerr and others have demonstrated that the Staffa Lava Formation flows were derived from the same parental magma as the (Mull) Plateau 'Group' (Kerr 1998; Kerr *et al.* 1999) but were severely contaminated by crustal material prior to eruption.

The Staffa Lava Formation flow field also hosts a number of sizeable sills and inclined sheet intrusions, including spectacular xenolithic sills, the so-called Loch Scridain Sill Complex (Chapter 8). Many of these sills are thought to have been emplaced at a shallow depth, contemporaneously with the formation of the flow field (Bailey *et al.* 1924; Preston *et al.* 1998).

The Formation crops out around the sea cliffs of SW Mull, for example on the Ross of Mull at Malcolm's Point and Ardtun, at Burg and The Wilderness on Ardmeanach, and on Staffa. Lavas of the Staffa Lava Formation may crop out at Bloody Bay, north of Tobermory. Significantly, the formation does not occur everywhere at the base of the lava pile; for example, it is absent at Beinn na h-Iolaire in west Mull and throughout Morvern (Kerr 1995b).

Fluvial systems that developed between eruptions deposited largely clastic sedimentary sequences that are collectively termed the Ardtun Conglomerate Member. These include laterally discontinuous conglomerate–sandstone sequences such as those at Ardtun on the north coast of the Ross of Mull, and laterally equivalent, overbank or lacustrine facies that give rise to siltstone–mudstone–coal–limestone sequences, well preserved on the south coast of the Ross of Mull (Boulter & Kvacek 1989).

On Ardmeanach, a pillowed facies at the base of the famous Macculloch's Tree Lava (Macculloch 1819) indicates that it was erupted into shallow water. The lava is underlain by interbedded hyaloclastite breccias, together with dark mudstones and siltstones that contain fragments of carbonaceous material (wood), in a fine-grained matrix. The preservation of a cast of an upright tree, 'Macculloch's Tree', is one of the remarkable features of the lava, with columnar joints being severely contorted (to a horizontal attitude) as they approach the vertical surface of the trunk.

Each of the sediment-volcanic 'pairs' can be depicted by stratigraphic logs and accompanying palaeo-geographic reconstructions, together with field photographs and this approach is adopted here, based upon the detailed study of Williamson & Bell (2012) (Figure 6-400; Figure 6-401; Figure 6-402; Figure 6-403; Figure 6-404; Figure 6-405; Figure 6-406; Figure 6-407; Figure 6-408; Figure 6-409; Figure 6-410; Figure 6-411; Figure 6-412; Figure 6-413; Figure 6-414; Figure 6-415; Figure 6-416; Figure 6-417; Figure 6-418; Figure 6-419; Figure 6-420; Figure 6-421; Figure 6-422; Figure 6-423; Figure 6-424; Figure 6-425; Figure 6-426; Figure 6-427; Figure 6-428; Figure 6-429; Figure 6-430; Figure 6-431; Figure 6-432; Figure 6-433; Figure 6-434; Figure 6-435; Figure 6-436; Figure 6-437; Figure 6-438; Figure 6-439; Figure 6-440; Figure 6-441; Figure 6-442; Figure 6-443; Figure 6-444; Figure 6-445; Figure 6-446; Figure 6-447; Figure 6-448; Figure 6-449; Figure 6-450; Figure 6-451; Figure 6-452; Figure 6-453; Figure 6-454; Figure 6-455; Figure 6-456; Figure 6-457; Figure 6-458; Figure 6-459; Figure 6-460; Figure 6-461; Figure 6-462;

Figure **6-463**; Figure 6-464; Figure 6-465).

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6.8.2.2 GS-A1

Figure 6-400; Figure 6-401; Figure 6-402:

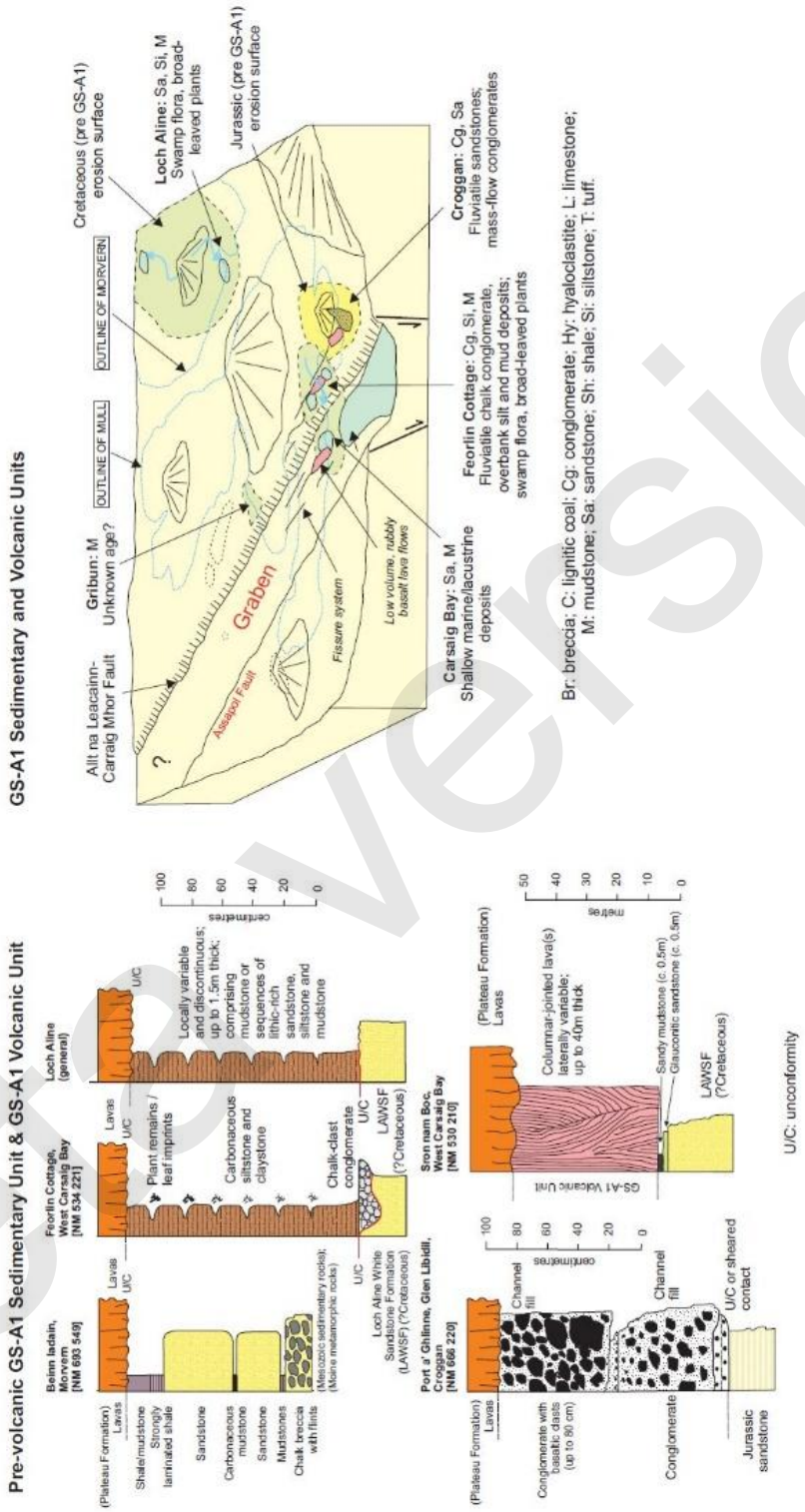


Figure 6-400: Lithological logs for pre-volcanic sedimentary rocks (?GS-A1 Sedimentary Unit), the GS-A1 Volcanic Unit, and a combined palaeogeographical/landscape interpretation for GS-A1 time (from Williamson & Bell 2012).

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Figure 6-401: GS-A1 (pre volcanic) Sedimentary Unit on the SE side of the Beinn Iadain ridge, Morvern. The section comprises (from base, upwards): brecciated chalk with flints (at hammer head), 2 cm black carbonaceous mudstone, 3 cm pale grey mudstone, 30 cm buff/grey sandstone, 1 cm carbonaceous mudstone (end of hammer shaft), 45 cm orange-weathering sandstone (directly above hammer), 10 cm laminated shale, 15 cm blocky shale, basaltic lava (top of view). Hammer *ca.* 30 cm.

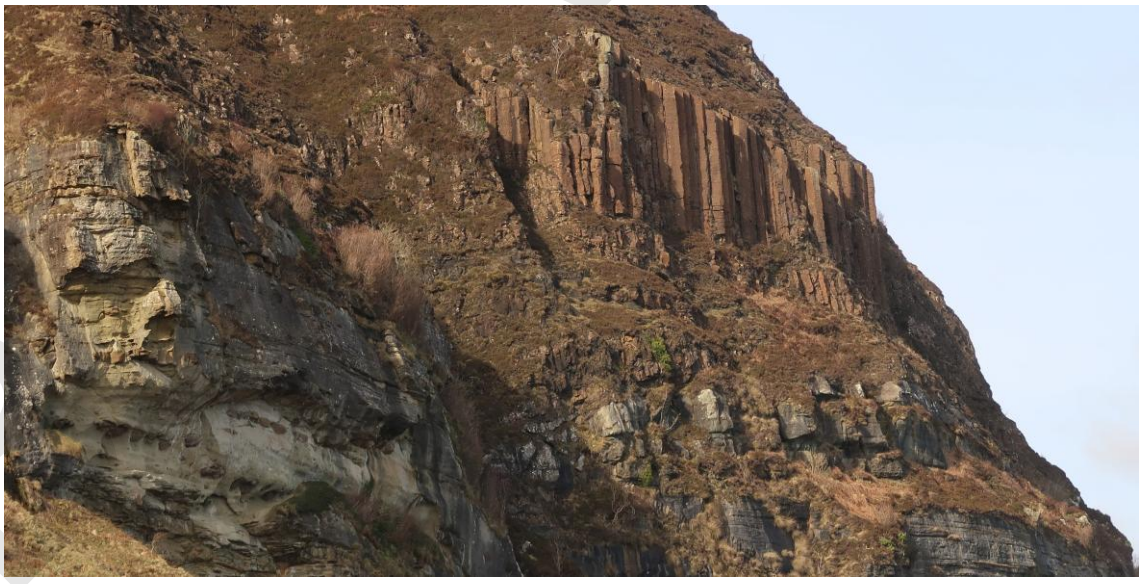


Figure 6-402: Columnar-jointed basaltic lavas overlying Upper Cretaceous and Lower Jurassic strata, Sròn nam Boc, west of Carsaig Bay, south coast of Brolass, SW Mull.

6.8.2.3 GS-A2

Figure 6-403; Figure 6-404; Figure 6-405; Figure 6-406; Figure 6-407; Figure 6-408; Figure 6-409:

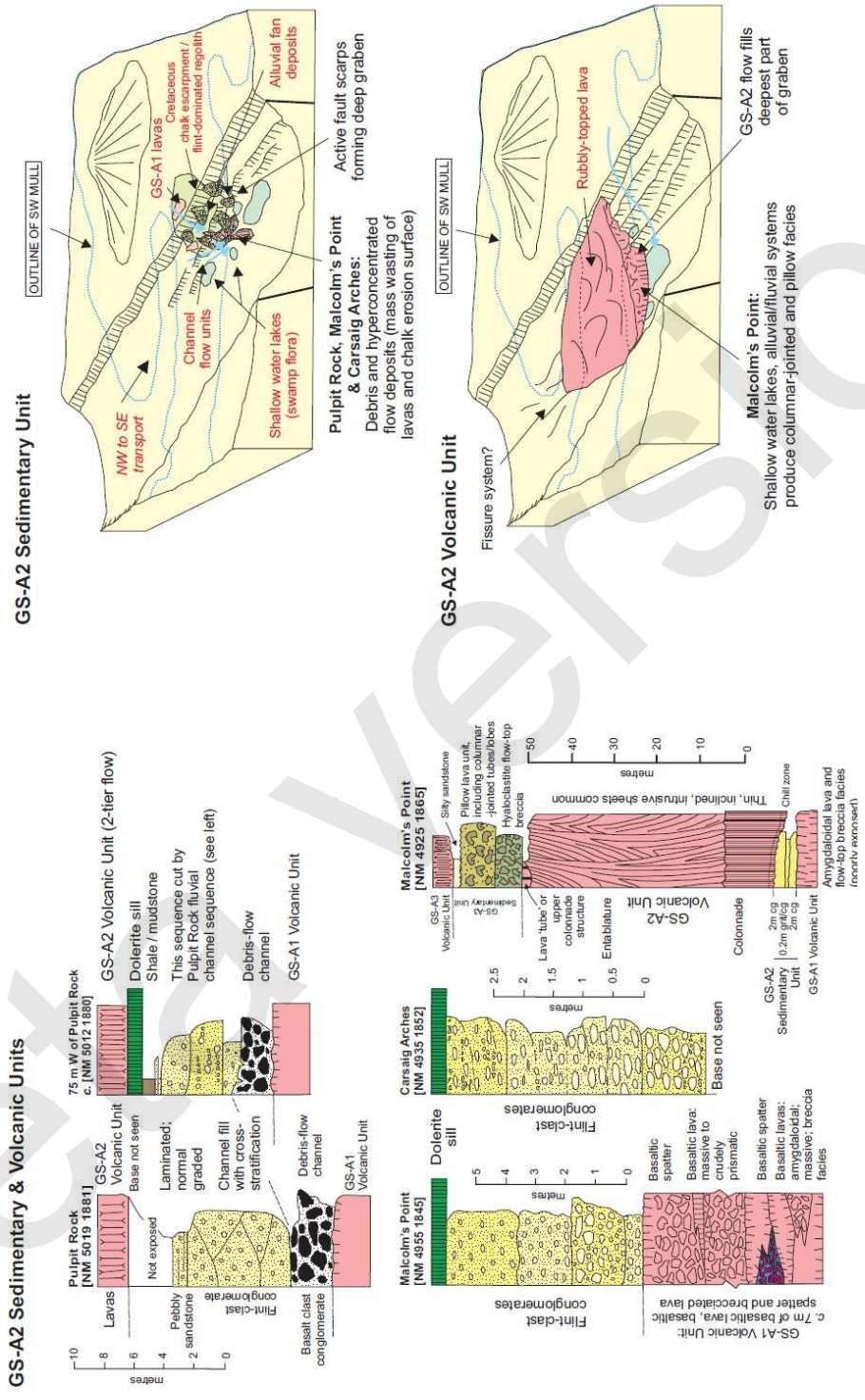


Figure 6-403: Lithological logs for the GS-A2 sedimentary and volcanic units and palaeo-geographical landscape interpretations (from Williamson & Bell 2012).

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Figure 6-404: Basaltic spatter at base of the GS-A2 sequence, Carsaig Arches, south coast of Brolass, SW Mull. Pen *ca*. 30 cm long.

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Figure 6-405: Flint clast conglomerate forming the upper part of the 'Pulpit Rock', east of Malcolm's Point, south coast of Brolass, SW Mull.



Figure 6-406: The Pulpit Rock, ENE of Malcolm's Point, south coast of Brolass, viewed towards the east. The section comprises, from the base upwards: GS-A1 basalt lavas, from base of exposure to base of prominent dark layer; with overlying GS-A2 Sedimentary Unit: a dark weathering, coarse-grained conglomerate with large angular basalt boulders and cobbles (*ca*. 2.4 m thick), a white-weathering, flint-dominated, clast-supported conglomerate with obvious cross-stratification (*ca*. 7 m), and dark-weathering, interbedded, coarse-grained sandstones and conglomerates, poorly exposed at the top of the sequence (at least 1 m).

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Figure 6-407: GS-A2 flint clast conglomerates and sandstones west of the Pulpit Rock, ENE of Malcolm's Point, south coast of Brolass, SW Mull. Hammer *ca.* 30 cm long.



Figure 6-408: GS-A2 sedimentary unit west of the Pulpit Rock, ENE of Malcolm's Point, south coast of Brolass: coarse conglomerate (C1; at least 2 m, base of view) with large angular basalt boulders and cobbles; bedded, coarse-grained sandstone (S1; up to 1.5 m) with angular to rounded clasts of basalt and flint; interbedded coarse-grained sandstone and conglomerate (S/C; up to 2.5 m, at hammer head) with rounded cobbles of flint, together with smaller, angular to rounded clasts of basalt and flint; and, bedded, coarse-grained sandstone (S2; up to 2 m, top of view) with angular to rounded clasts of flint and basalt and rare large boulders of flint. Hammer shaft *ca*. 30 cm long.

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Figure 6-409: The GS-A2 Sedimentary Unit west of the Pulpit Rock, ENE of Malcolm's Point, south coast of Brolass. The section comprises (from base, upwards): GS-A1 basaltic lavas; GS-A2 Sedimentary Unit: coarse conglomerate with large angular basalt boulders and cobbles, bedded coarse sandstone, interbedded coarse sandstone and conglomerate, bedded coarse sandstone, and up to 1.5 m of laminated siltstone and mudstone (*ca*. 0.85 m; S/M) intruded by a thin sill, below a GS-A2 basaltic lava. Graham McLeod for scale.

Beta Version

6.8.2.4 GS-A3

Figure 6-410; Figure 6-411; Figure 6-412; Figure 6-413; Figure 6-414:



Figure 6-410: The GS-A3 volcanic sequence in the Carsaig cliff section at Malcolm's Point. The base of the section, at the Carsaig Arches (bottom middle), is intruded by dolerite sills. The cliff is approximately 280 m high.

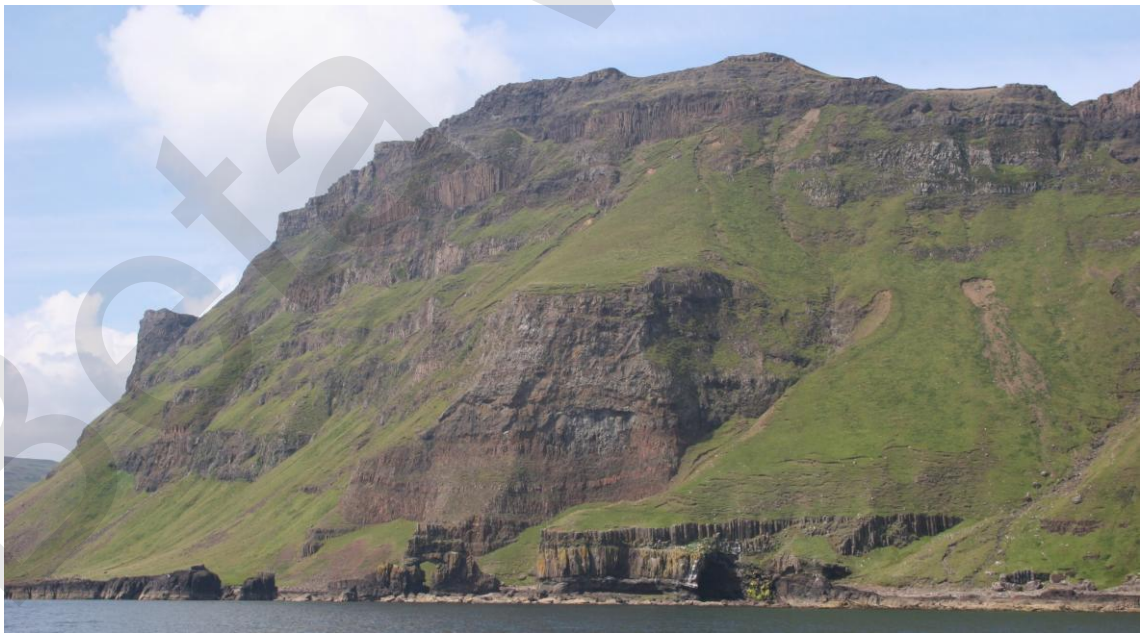


Figure 6-411: The GS-A3 volcanic sequence in the Carsaig cliff section at Malcolm's Point. The base of the section, at the Carsaig Arches (bottom middle), is intruded by dolerite sills. The cliff is approximately 280 m high.

Beta version



Figure 6-412: The GS-A3 volcanic sequence of the Binnein Ghorrie cliff section, south coast of Brolass, viewed east from the west side of Tràigh Cadh' an Easa'. The sequence comprises columnar-jointed, prismatic-jointed and rubbly compound lavas, all cut by thin, anastomosing sheets of basalt and dolerite. Interbedded with the lavas are thin laterally restricted beds of sandstone, siltstone, mudstone and clastic limestone, which tend to be paler and more weathered than the lavas. The cliff is approximately 280 m high.

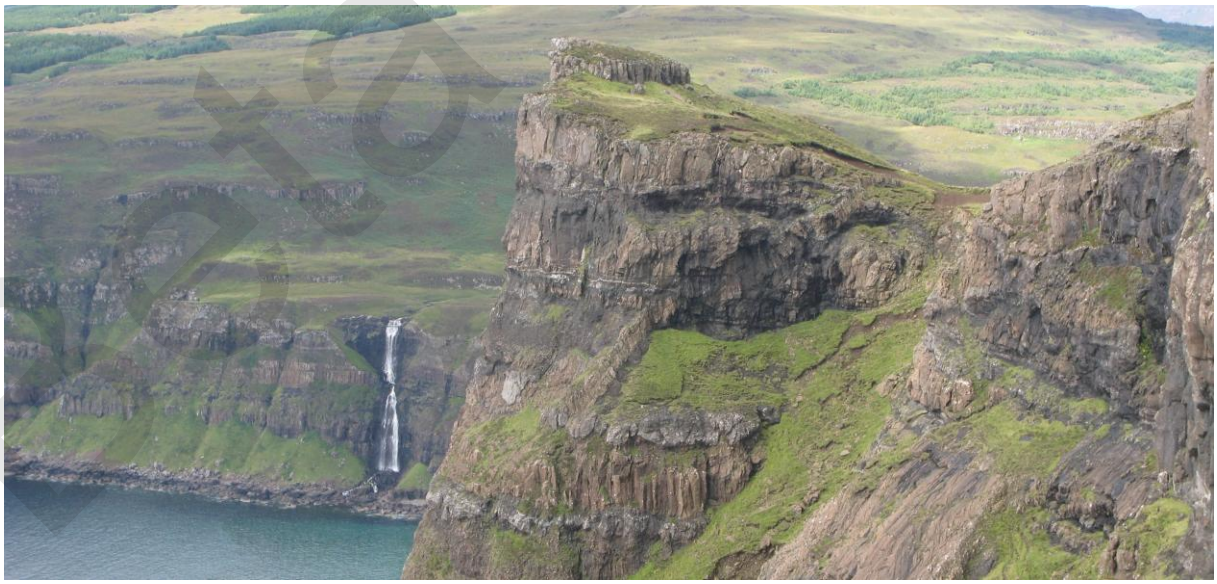


Figure 6-413: The GS-A3 volcanic sequence of the Binnein Ghorrie cliff section, south coast of Brolass, viewed towards Tràigh Cadh' an Easa' (waterfall).

Pre-Version

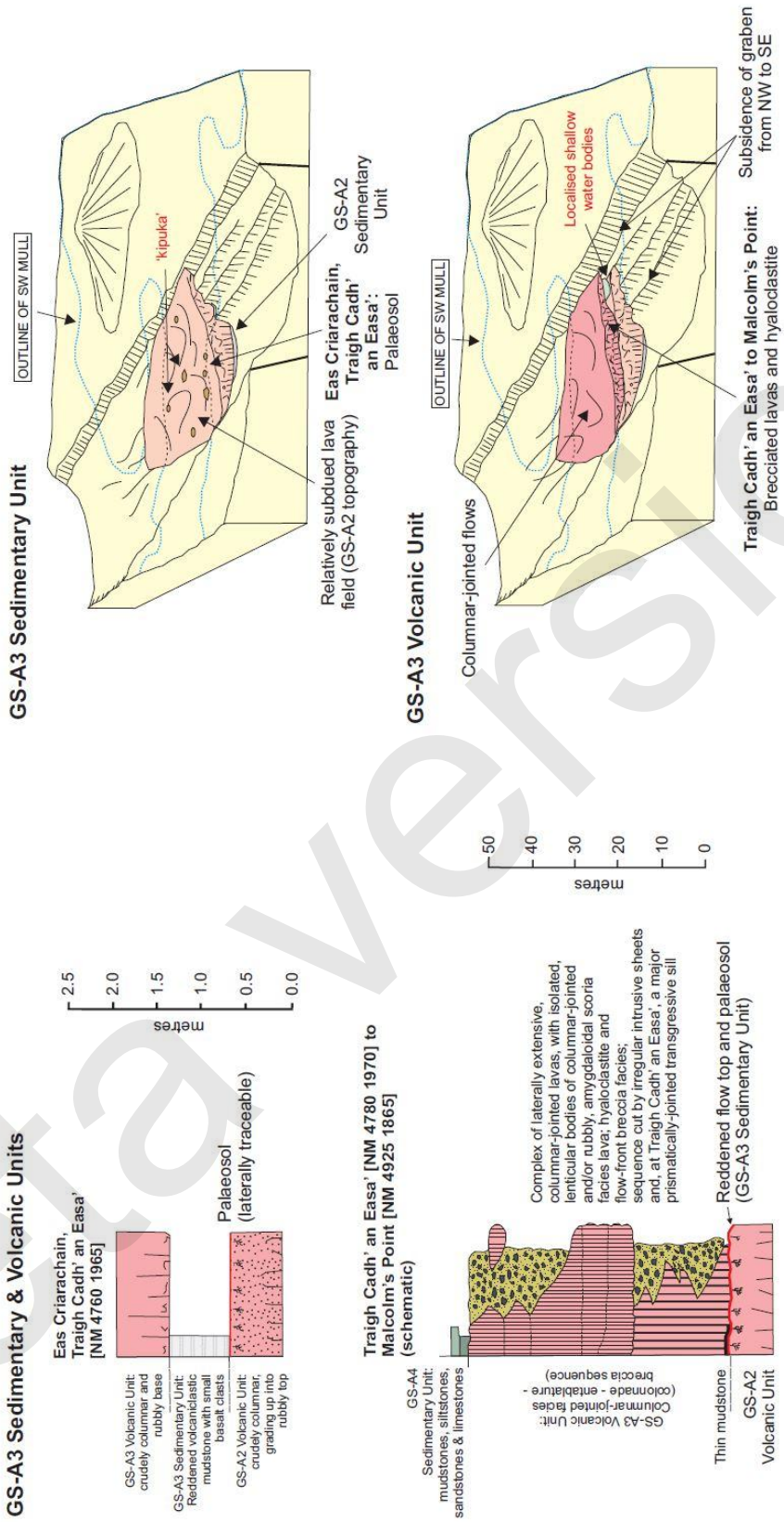


Figure 6-414: Lithological logs for the GS-A3 sedimentary and volcanic units and palaeogeographical landscape interpretations (from Williamson & Bell 2012).

Beta version

6.8.2.5 GS-A4

Figure 6-415; Figure 6-416; Figure 6-417; Figure 6-418:

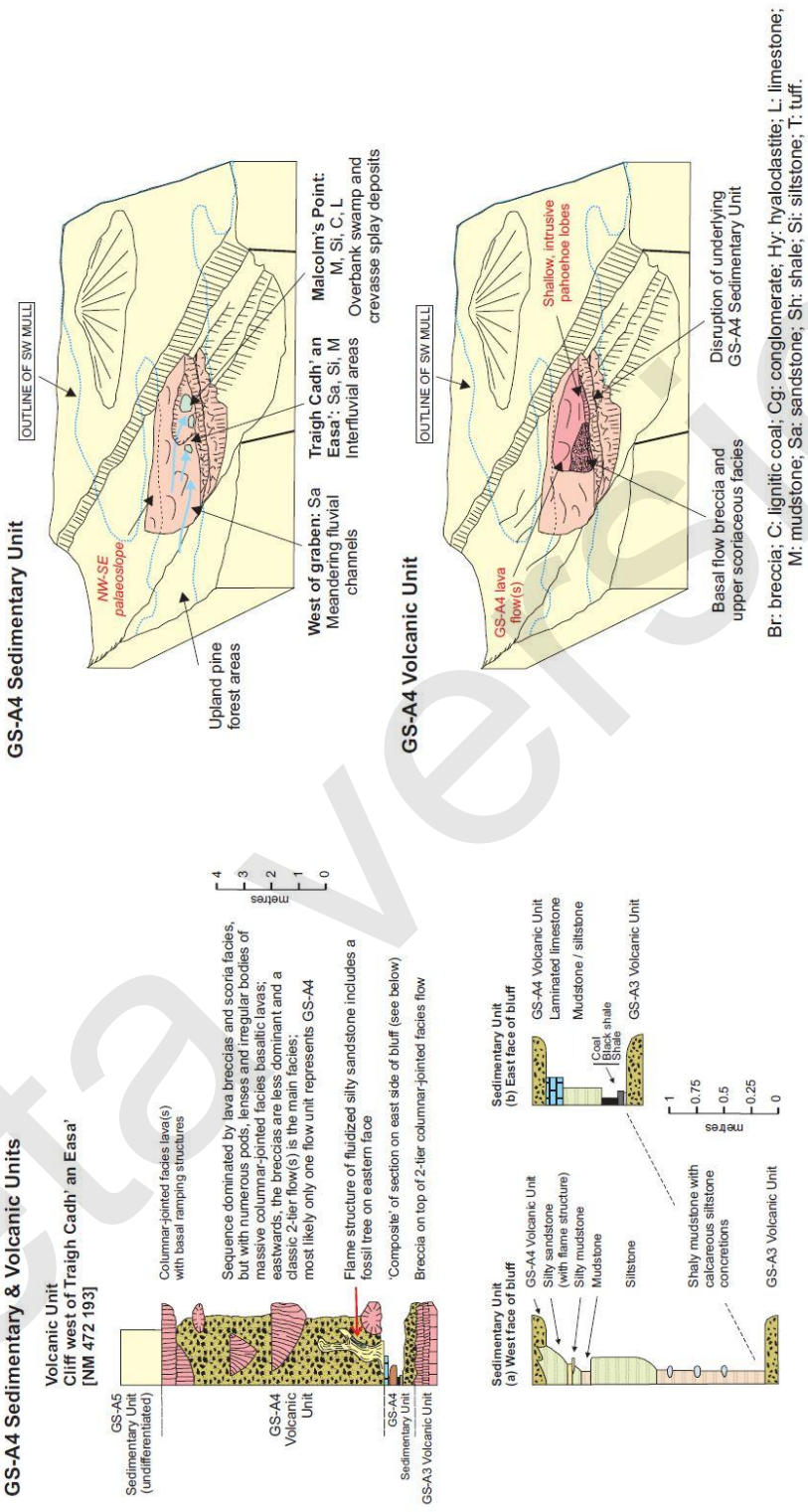


Figure 6-415: Lithological logs for the GS-A4 sedimentary and volcanic units and palaeogeographical landscape interpretations (from Williamson & Bell 2012).

Beta version



Figure 6-416: Deformed lenses and pods of GS-A4 sandstone and siltstone caught up in the base of a prismatic-jointed basaltic lava on the west side of Tràigh Cadh' an Easa'. Deformation of the unlithified sedimentary material was partly due to shearing along the base of the lava as it advanced over the land surface. Ian Williamson for scale.



Figure 6-417: Disrupted GS-A4 coal-mudstone sequence below the GS-A4 Volcanic Unit, the 'Carsaig Tree Lava'. The sedimentary sequence is intruded by a thin sheet of basalt, possibly related to the overlying columnar-jointed lava. Hammer shaft *ca.* 30 cm long.

Br



Figure 6-418: The Carsaig Tree, a *ca.* 2.5 m wide and *ca.* 14 m tall fossil tree cast, set within a columnar-jointed GS-A4 basaltic lava, the Carsaig Tree Lava, in the cliff section *ca.* 300 m NW of Carsaig Arches. The columnar joints around the cast are deflected, implying that the tree was capable of modifying the local isotherms and causing cooling joints to form normal to the length of the trunk. The flow that enveloped the tree rests directly on a thin coal-mudstone unit. Person for scale.

Beta Version

6.8.2.6 GS-A5

Figure 6-419; Figure 6-420; Figure 6-421; Figure 6-422; Figure 6-423; Figure 6-424; Figure 6-425; Figure 6-426; Figure 6-427; Figure 6-428; Figure 6-429; Figure 6-430; Figure 6-431; Figure 6-432; Figure 6-433; Figure 6-434; Figure 6-435; Figure 6-436; Figure 6-437; Figure 6-438; Figure 6-439; Figure 6-440; Figure 6-441; Figure 6-442; Figure 6-443; Figure 6-444; Figure 6-445; Figure 6-446; Figure 6-447; Figure 6-448:

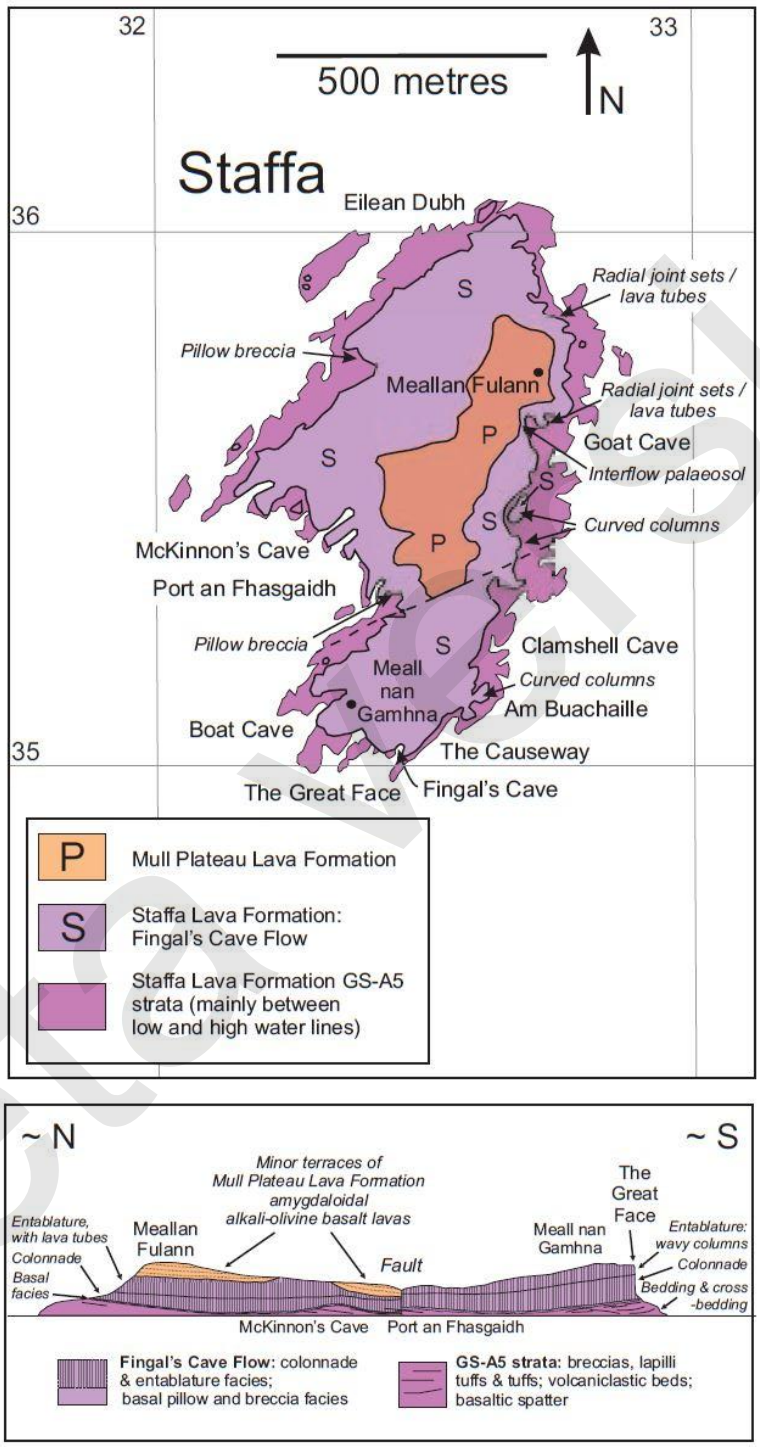


Figure 6-419: Simplified geological map and schematic cross-section with place names for Staffa (from Williamson & Bell 2012).

Beta Version

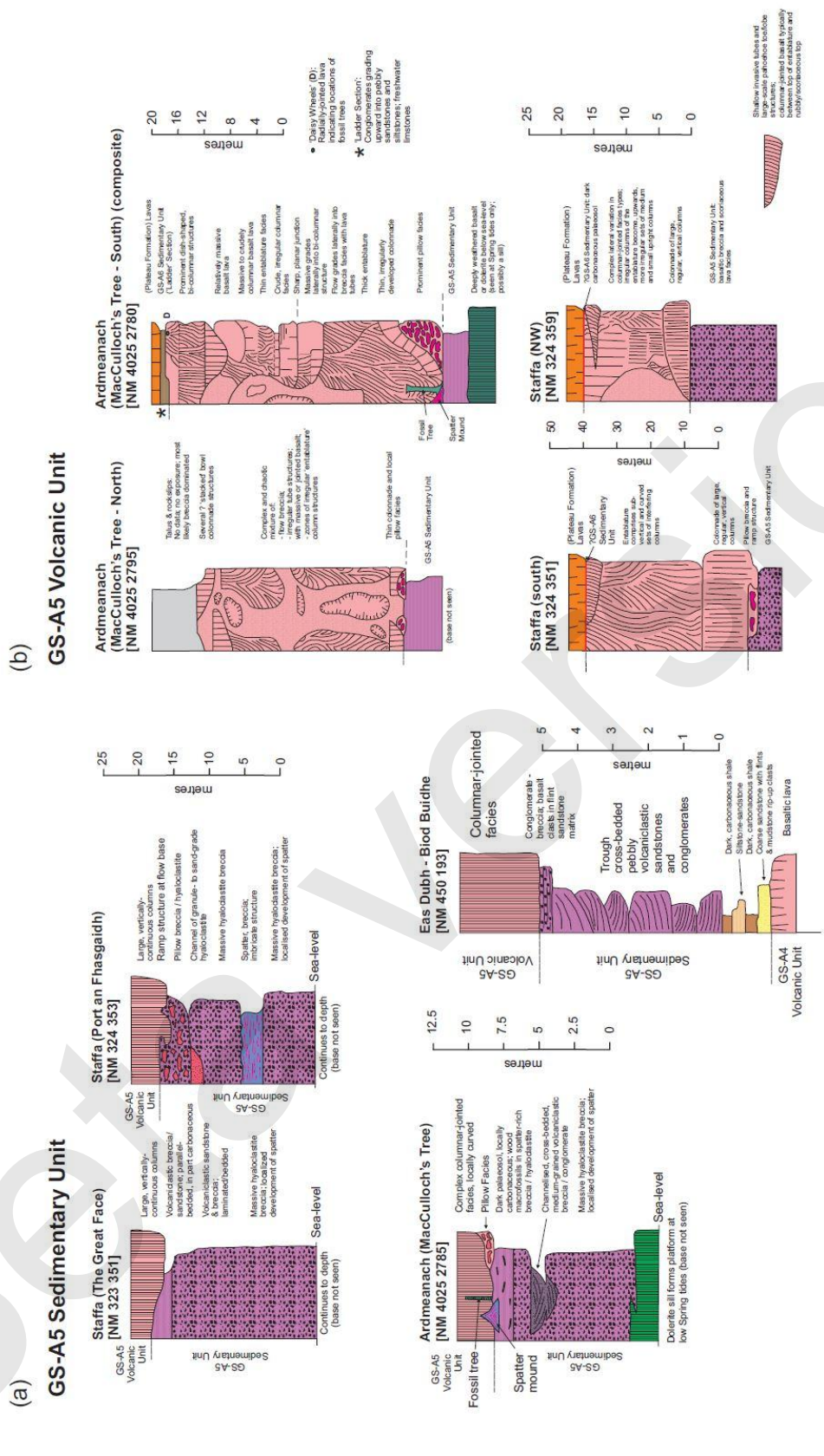
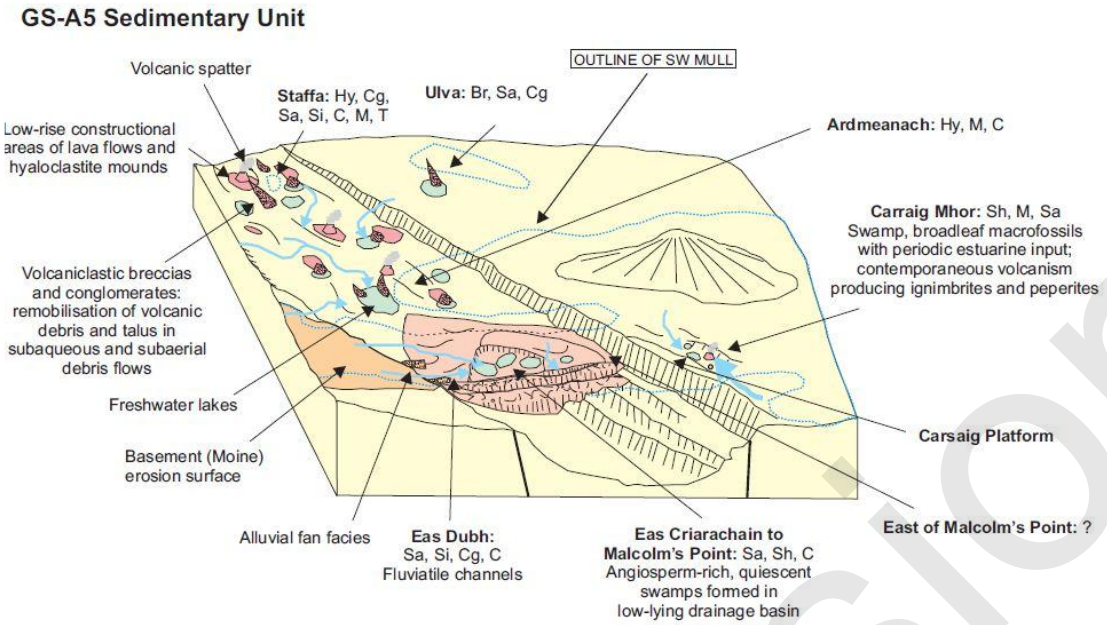


Figure 6-420: Lithological logs for the GS-A5 Sedimentary Unit and the GS-A5 Volcanic Unit (from Williamson & Bell 2012).

Beta version

(c)



Br: breccia; C: lignitic coal; Cg: conglomerate; Hy: hyaloclastite; L: limestone; M: mudstone; Sa: sandstone; Sh: shale; Si: siltstone; T: tuff.

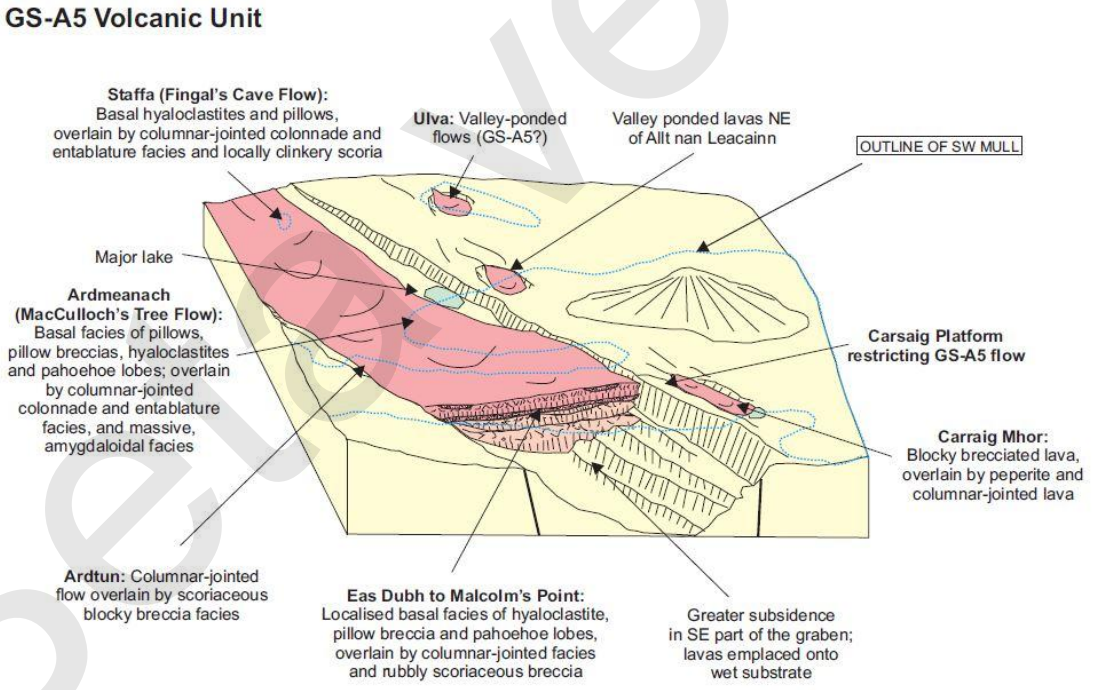


Figure 6-421: Palaeogeographical landscape interpretations for GS-A5 time (from Williamson & Bell 2012).

Beta version



Figure 6-422: The Great Face, SW Staffa, west of Fingal's Cave. The main crag comprises the classic colonnade - entablature doublet of the Fingal's Cave Lava, overlying GS-A5 bedded pyroclastic–volcaniclastic deposits. The lava is approximately 50 m thick (although only *ca*. 30 m is preserved on the Great Face). The rubbly top of the lava is absent locally. The base of the lava is sharp and planar, and dips at a shallow angle towards the east. The cliff is *ca*. 42 m high. Person on cliff top for scale.



Figure 6-423: Lava sequence, west Staffa.

Beta version



Figure 6-424: Lava sequence, west Staffa.



Figure 6-425: Lava-rag and spatter deposit from the GS-A5 pyroclastic-volcaniclastic sequence below the Fingal's Cave Lava, SW Staffa. This bed crops out below the Great Face and is at least 20 m thick, although the base is not seen. Crenulation and fold-like structures are preserved on the surfaces of the volcanic fragments. Compass is *ca*. 10 cm long.



Figure 6-426: Lava-rag and spatter deposit from the GS-A5 pyroclastic-volcaniclastic sequence below the Fingal's Cave Lava, SW Staffa. This bed crops out below the Great Face and is at least 20 m thick, although the base is not seen. Crenulation and fold-like structures are preserved on the surfaces of the volcanic fragments. Compass is *ca*. 10 cm long.

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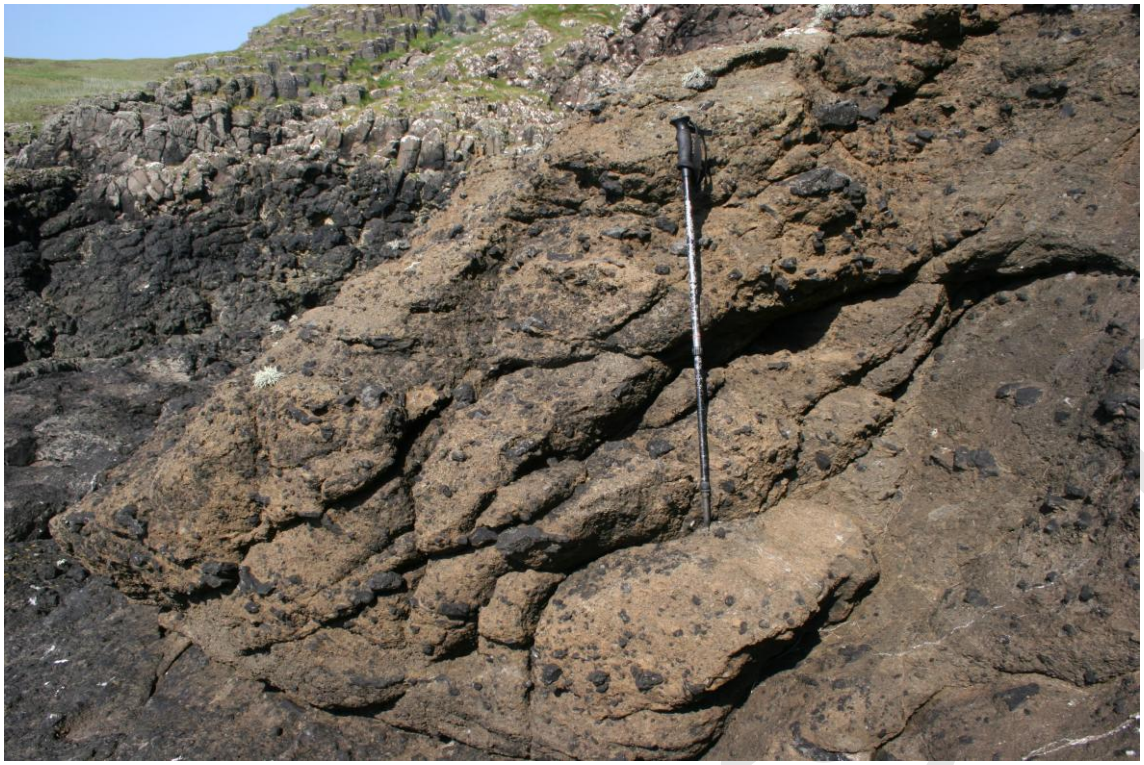


Figure 6-427: Detail of hyaloclastite unit, Port an Fhasgaidh, below the Fingal's Cave Lava, Staffa. Pole *ca.* 1 m long.



Figure 6-428: Detail of hyaloclastite unit, Port an Fhasgaidh, below the Fingal's Cave Lava, Staffa. Lens cap *ca.* 8 cm across.



Figure 6-429: Coastal section, with Macculloch's Tree Lava and underlying pyroclastic-volcaniclastic strata, Ardmeanach. Fossil tree, left of centre, above pale beach cobbles.



Figure 6-430: Bedded pyroclastic–volcaniclastic strata of GS-A5 Sedimentary Unit below the Macculloch's Tree Lava, *ca*. 60 m NW of Macculloch's Tree, Ardmeanach. View is towards SE. The unit contains lava-rags and spatter, together with angular fragments of basalt, all set in an ash-dominated matrix. Cross-bedding and grading suggest some form of reworking. The basal facies of the lava comprises invasive, tube-like structures, above which is the main colonnade of the lava. These columns are deformed at the top, possibly indicating (late-stage?) movement or flow towards the SE. The colonnade has a sharp contact with the overlying irregular entablature of the lava. The small bluff of pyroclastic– volcaniclastic strata is *ca*. 3 m high.



Figure 6-431: Bedded pyroclastic–volcaniclastic strata of GS-A5 Sedimentary Unit below the Macculloch's Tree Lava, Rubha na h-Uamha, Ardmeanach. Within these beds, large fragments of woody (now charcoal) material, some several tens of centimetres long, have accumulated as drifts within channels. Compass *ca*. 10 cm long.



Figure 6-432: Bedded pyroclastic–volcaniclastic strata of GS-A5 Sedimentary Unit below the Macculloch's Tree Lava, Rubha na h-Uamha, Ardmeanach. Within these beds, large fragments of woody (now charcoal) material, some several tens of centimetres long, have accumulated as drifts within channels. Compass *ca*. 10 cm long.



Figure 6-433: Thin, discontinuous slab of coal within hyaloclastite unit below the Macculloch's Tree Lava, Rubha na h-Uamha, Ardmeanach. Compass *ca.* 10 cm long.



Figure 6-434: Dome-like accumulation of welded basaltic spatter, left of centre, below the Macculloch's Tree Lava on the raised promontory *ca.* 30 m NW of Macculloch's Tree.

Beu



Figure 6-435: Dome-like accumulation of welded basaltic spatter, left of centre, below the Macculloch's Tree Lava on the raised promontory *ca*. 30 m NW of Macculloch's Tree.



Figure 6-436: Dome-like accumulation of welded basaltic spatter below the Macculloch's Tree Lava on the raised promontory *ca*. 30 m NW of Macculloch's Tree. The deposit has a well-developed fabric and is overlain by *ca*. 1–2 cm of coal-mudstone, overlain in turn by the invasive basal portion of the Macculloch's Tree Lava, containing various tube-like structures. John Faithfull for scale.



Figure 6-437: Detail of dome-like accumulation of welded basaltic spatter below the Macculloch's Tree Lava on the raised promontory *ca*. 30 m NW of Macculloch's Tree. Compass *ca*. 20 cm long.

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Figure 6-438: Section through the lower portion of the MacCulloch's Tree Lava, north of the Tree locality at Druim na h-Uamha, comprising radially jointed tubes within the basal breccia facies of the lava. Overlying this, the lava consists of a highly irregular columnar-jointed colonnade. Below are bedded pyroclastic–volcaniclastic strata of the GS-A5 Sedimentary Unit. The cliff is *ca*. 25 m high, with John Faithfull for scale (bottom right).



Figure 6-439: Detail of base of Macculloch's Tree Lava, underlain by a thin layer of low-grade coal, below which is a bed of hyaloclastite. GPS unit *ca*. 10 cm long.



Figure 6-440: Pillow facies of the Macculloch's Tree Lava, *ca*. 100 m south of Macculloch's Tree. A thickness of at least 10 m of pillow- and tube-like lava overlies the basal invasive facies of the lava. The classical colonnade-entablature couplet is absent. Eruption of the flow into water is implied by the development of pillow structures. John Faithfull for scale.

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Figure 6-441: Macculloch's Tree, west coast of Ardmeanach, north of the prominent twin waterfalls. This upright structure is *ca*. 2 m across, with a preserved height of *ca*. 18 m, and is considered to have been a taxodiaceous tree. The base is not exposed, and the lowermost *ca*. 2 m is a cast composed of mineralized woody material, preserving bark textures and some internal structure. The remaining *ca*. 16 m of the tree is a slightly ovoid mould. The columnar joints in the vicinity of the mould are deflected, implying modification of local isotherms causing joints to form orthogonal/normal to the trunk axis. John Faithfull and Graham McLeod for scale.



Figure 6-442: Bark imprint, Macculloch's Tree, west coast of Ardmeanach. Compass *ca.* 10 cm long.



Figure 6-443: Bark imprint of Macculloch's Tree, west coast of Ardmeanach.

Beta Version



Figure 6-444: A 'daisy wheel' structure within the Macculloch's Tree Lava, between Carraig a' Mhinisteir and Garadh na Sroine, Ardmeanach. The radiating columnar joints may reflect cooling induced by a (now absent) upright tree, similar to Macculloch's Tree. The 'daisy wheel' is a plan view whereas MacCulloch's Tree (Figure 6.397) is a vertical section. Ian Williamson and Graham McLeod for scale.



Figure 6-445: Conglomerates and sandstones of the Ladder Sequence, south of Macculloch's Tree, west coast of Armeanach. Hammer *ca*. 50 cm long.



Figure 6-446: Cliff section at Carraig Mhòr, east of Carsaig Bay, south Brolass, consisting of four main lithologies. At the base of the cliff section is a GS-A5 sandstone and carbonaceous siltstone couplet. Overlying these strata is a *ca*. 10 m thick blocky brecciated lava (GS-A5), highly weathered and difficult to further differentiate. This is stratigraphically overlain by *ca*. 10 m of stratiform, graded peperite, the base of which fills an irregular topography in the surface of the weathered lava beneath. An auto-intrusive basaltic lava with well-developed columnar joints caps the peperite. The irregular lower surface of this fills a series of channels, drowning the palaeo-topography. Overlying tabular/sheet basalt lavas of the Plateau Formation give rise to the typical trap topography of the lava field. The cliff is *ca*. 35 m high.

Beta Version



Figure 6-447: The peperite at Carraig Mhòr, south coast of Brolass, is a localised sedimentary–volcanic facies of the GS-A5 Volcanic Unit, involving the complex blending of pore-water -rich, unlithified sediment with magma. It comprises altered, pale brown-green igneous clasts of basaltic composition, which display a variety of sub-angular, through sub-rounded, to curvilinear and crenulate fluidal morphologies. Some clasts are fractured, with irregular margins commonly displaying a jigsaw-fit, contrasting with the 'bulbous' and 'finger-like' projections of others. Most clasts are of highly altered, semi-hyaline igneous material. A small proportion have well-developed quench-textured rims. The clasts are enclosed in a dark brown finely laminated matrix of silt- and clay-grade material. Laminae are defined by grain size and colour and are typically contorted and concordant with clast margins. The matrix material also fills late-stage fractures that have penetrated some clasts. Compass *ca*. 10 cm long.

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Figure 6-448: Ignimbrite (at hammer), interbedded with sandstones, siltstones, mudstones and shales within the GS-A5 Sedimentary Unit exposed on the foreshore at Carraig Mhòr, east of Carsaig Bay, south coast of Brolass. Towards the top of the ignimbrite, there is a significant proportion of intermixed carbonaceous and coaly material. Ungraded peperites form part of the sequence. The entire foreshore sequence is invaded by irregular dolerite intrusions. The cliff at the back of the foreshore comprises a thin sandstone-siltstone couplet, overlain by blocky, brecciated basalt lava, graded peperite and columnar-jointed basaltic lava. Hammer shaft *ca*. 30 cm long.

Beta Version

6.8.2.7 GS-A6

Figure 6-449; Figure 6-450; Figure 6-451; Figure 6-452; Figure 6-453; Figure 6-454; Figure 6-455; Figure 6-456; Figure 6-457; Figure 6-458; Figure 6-459; Figure 6-460; Figure 6-461; Figure 6-462;

Figure **6-463**; Figure 6-464; Figure 6-465:

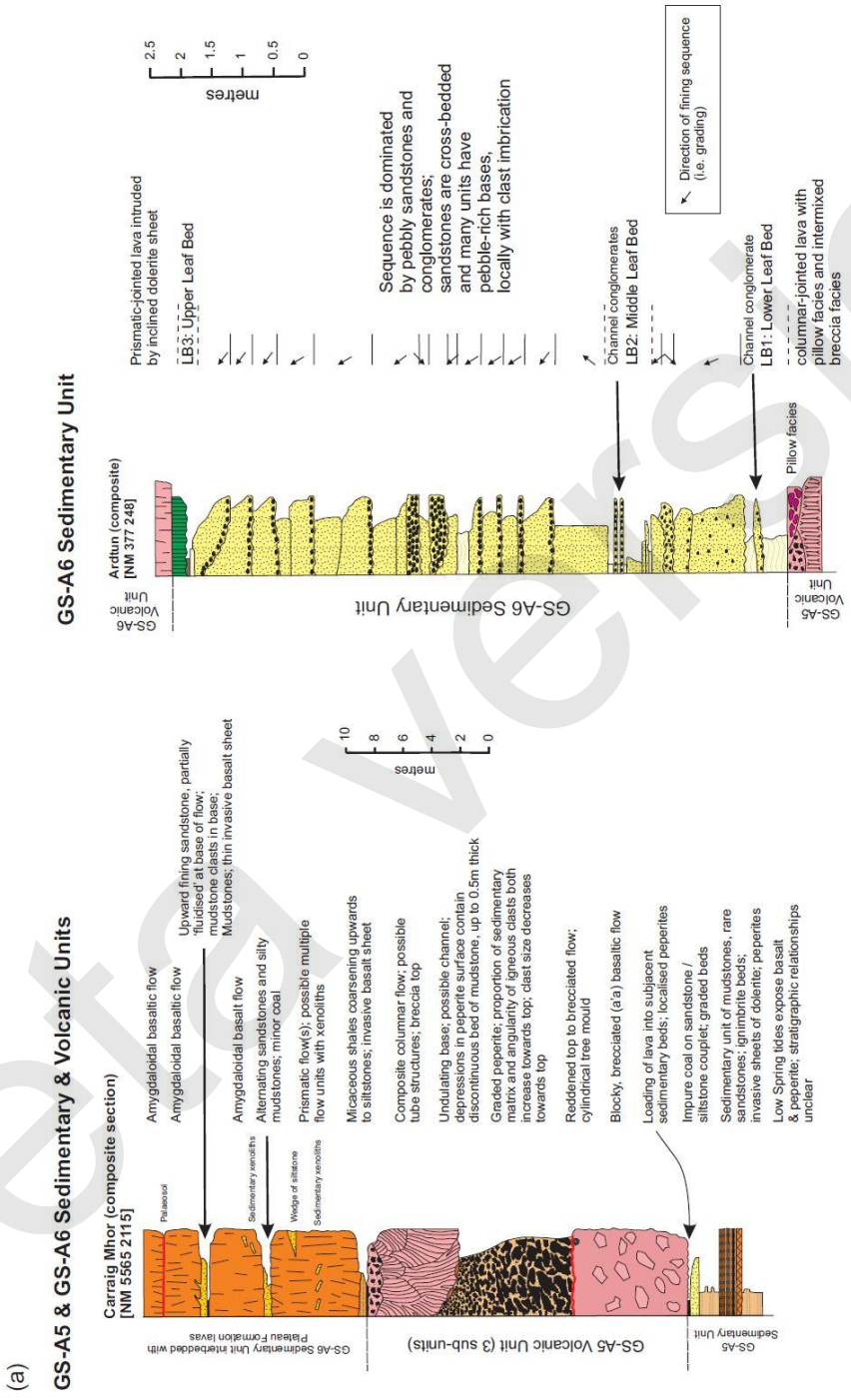


Figure 6-449: Lithological logs for the GS-A5/A6 Sedimentary and Volcanic Units (from Williamson & Bell 2012).

Beta version

(b)

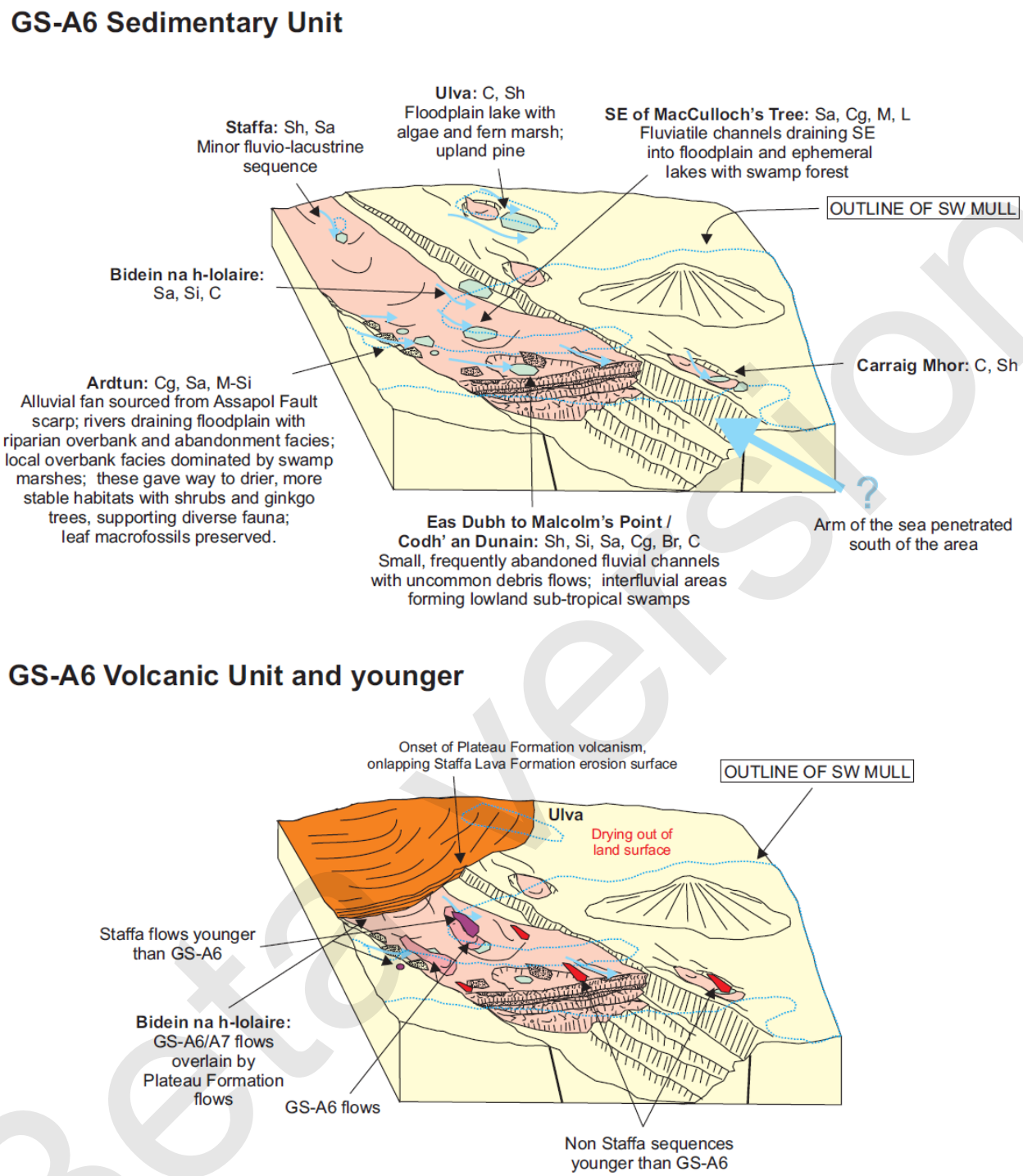


Figure 6-450: Palaeogeographical landscape interpretation for GS-A6 and younger (chrono-stratigraphic) intervals (from Williamson & Bell 2012).

Beta version

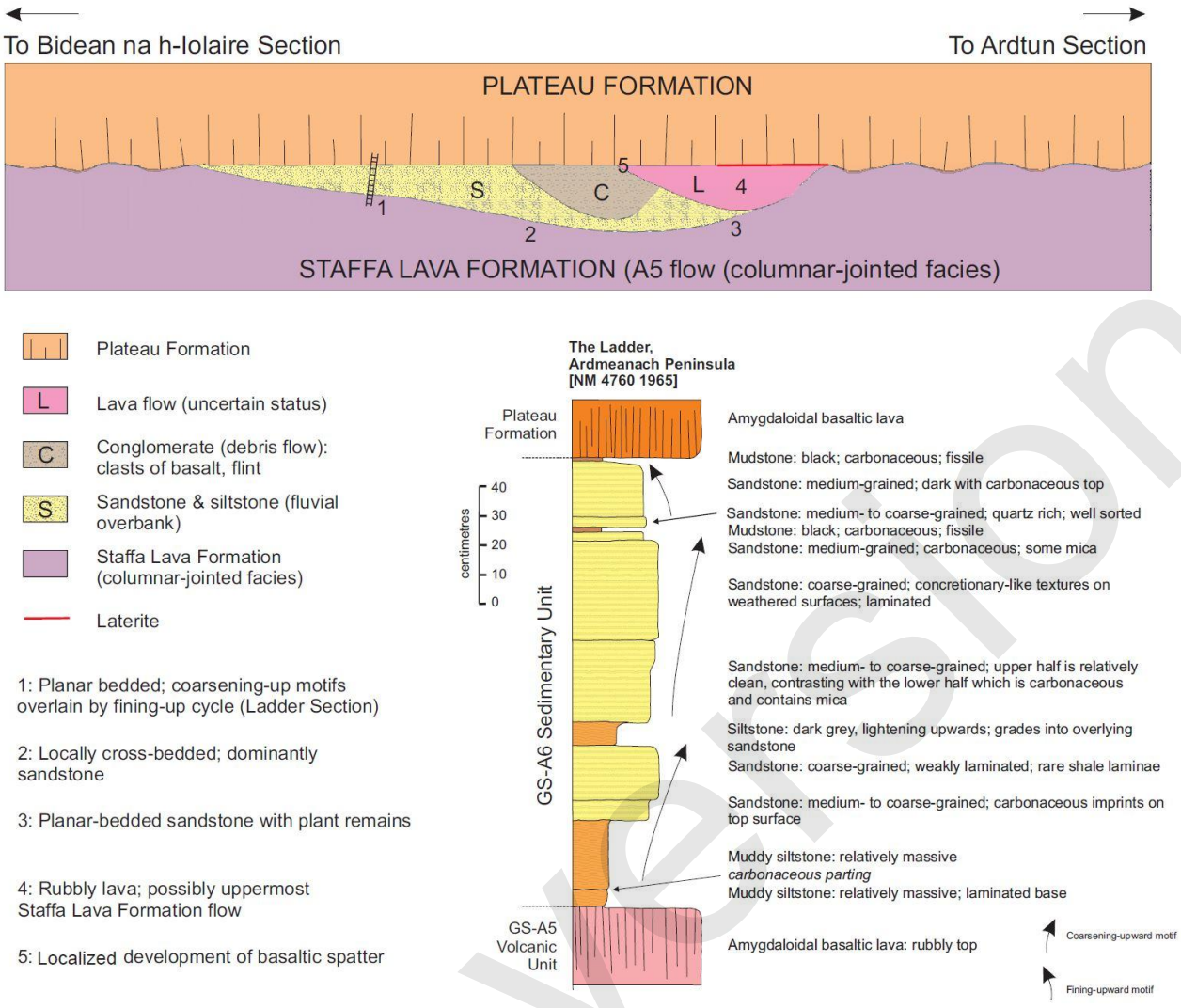


Figure 6-451: Schematic cross-section and lithological log for the GS-A6 Sedimentary Unit at The Ladder, south of Macculloch's Tree, Ardmeanach (from Williamson & Bell 2012).

Beta version

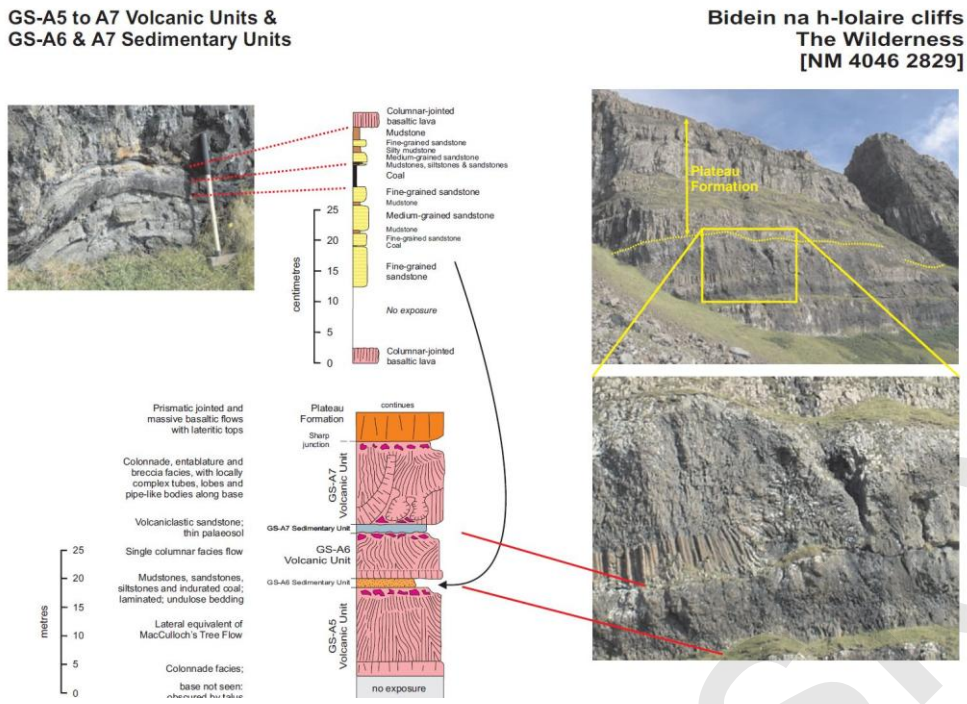


Figure 6-452: GS-A5 to GS-A7 volcanic units and GS-A6 and GS-A7 sedimentary units at Bidein na h-Iolaire, The Wilderness (north of Macculloch's Tree), Ardmeanach (from Williamson & Bell 2012).



Figure 6-453: Exposure of the GS-A6 Ardtun Leaf Beds on the west side of the gully, Sloch an Uruisge, on the Loch Scridain-facing coastline north of Ardtun. The sequence comprises flint-clast-dominated conglomerates interbedded with sandstones, siltstones, shales and mudstones that include the Ardtun Leaf Beds (recessed gap). The sedimentary sequence is capped by a platy, orange-weathering, crudely columnar-jointed basaltic lava belonging to the GS-A6 Volcanic Unit. The upper conglomerate–sandstone–siltstone unit is *ca*. 4 m thick.

Browser version



Figure 6-454: Detail of Ardtun Leaf Beds, west side of gully, Sloch an Uruisge, Loch Scridain.



Figure 6-455: Ardtun Leaf Beds, east side of Sloch an Uruisge, south side of Loch Scridain.

Draft



Figure 6-456: Detail of the Ardtun Leaf Beds on west side of Slochd an Uruisge, south side of Loch Scridain. Pole *ca*. 1 m long.



Figure 6-457: Columnar-jointed lava with well developed, but typically curved, colonnade columns between Carraig Chorrach and Biod an Sgairbh on the Loch Scridain-facing coastline north of Ardtun. The entablature is complex, comprising small radiating and fanning columns, and is overlain by blocky breccia. This GS-A5 lava is at least 15 m thick and is similar to the Fingal's Cave and Macculloch's Tree lavas. Height of bench formed by the lava is *ca*. 15 m.

Bookversion

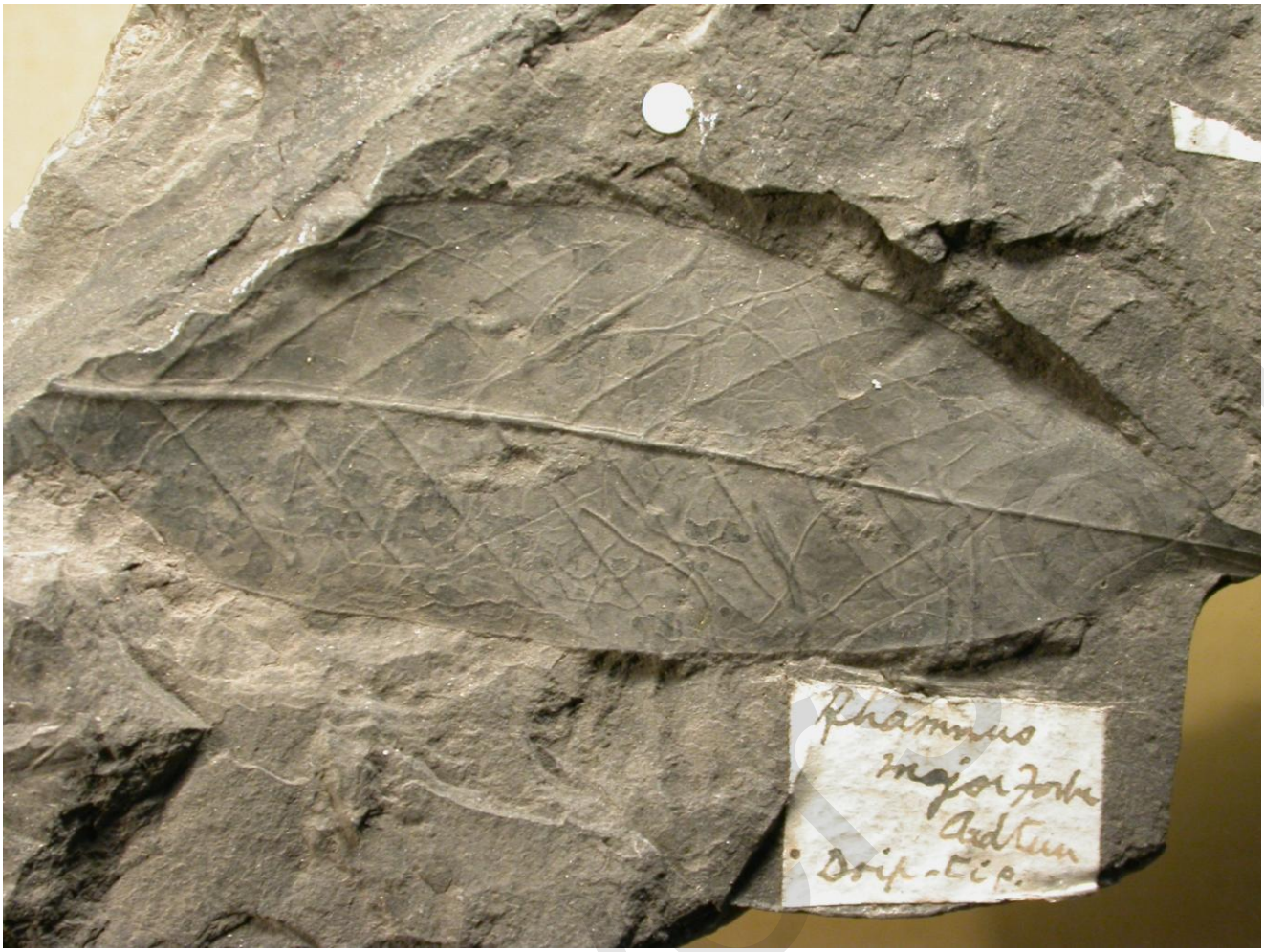


Figure 6-458: ***Camptodromites major*** **(Johnson) Boulter & Kvacek (1989). A simple leaf with smooth to sinuous margins and a tapered termination forming a drip-tip. A strong mid-rib gives off a series of parallel secondary veins rising from a leaf base that is slightly asymmetrical. The leaf is thought to have been derived from a flowering plant that was probably evergreen and is an extinct member of a family of plants that includes oaks and chestnuts.**



Figure 6-459: Leaf imprints from the Ardtun Leaf Beds, SW Mull.

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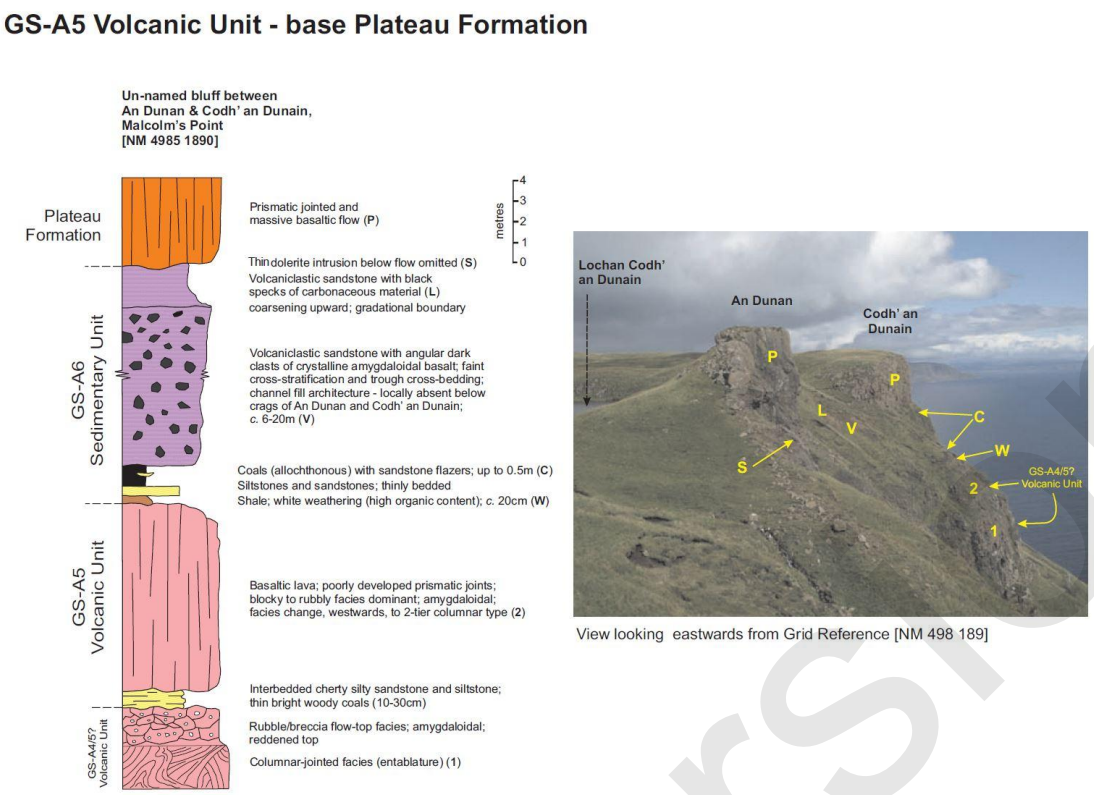


Figure 6-460: View eastwards from An Dùnan (SE of Beinn an Aoinidh, south coast of Brolass) and schematic log of the section. The upper part of the cliff consists of the GS-A6 Sedimentary Unit overlain by a remnant of a thick, prismatically jointed, pale-weathering lava of the Mull Plateau Lava Formation (from Williamson & Bell 2012).



Figure 6-461: Detail of the sequence at An Dùnan, SE of Beinn an Aoinidh, south coast of Brolass, capped by a remnant of a prismatic-jointed lava. Forming a small ledge, below, is a pale-weathered coal-mudstone-siltstone sequence.

Pre-publication version



Figure 6-462: Coal-mudstone-siltstone sequence interbedded with columnar-jointed basaltic lavas at An Dùnan, SE of Beinn an Aoinidh, south coast of Brolass, SW Mull.



Figure 6-463: Detail of the coal-mudstone-siltstone sequence at An Dùnan, SE of Beinn an Aoinidh, south coast of Brolass, capped by a prismatic-jointed lava.

Pre-Version



Figure 6-464: Detail of coal-mudstone-siltstone sequence below An Dùnan, SE of Beinn an Aoinidh, south coast of Brolass, SW Mull. Pole *ca*. 1 m long.

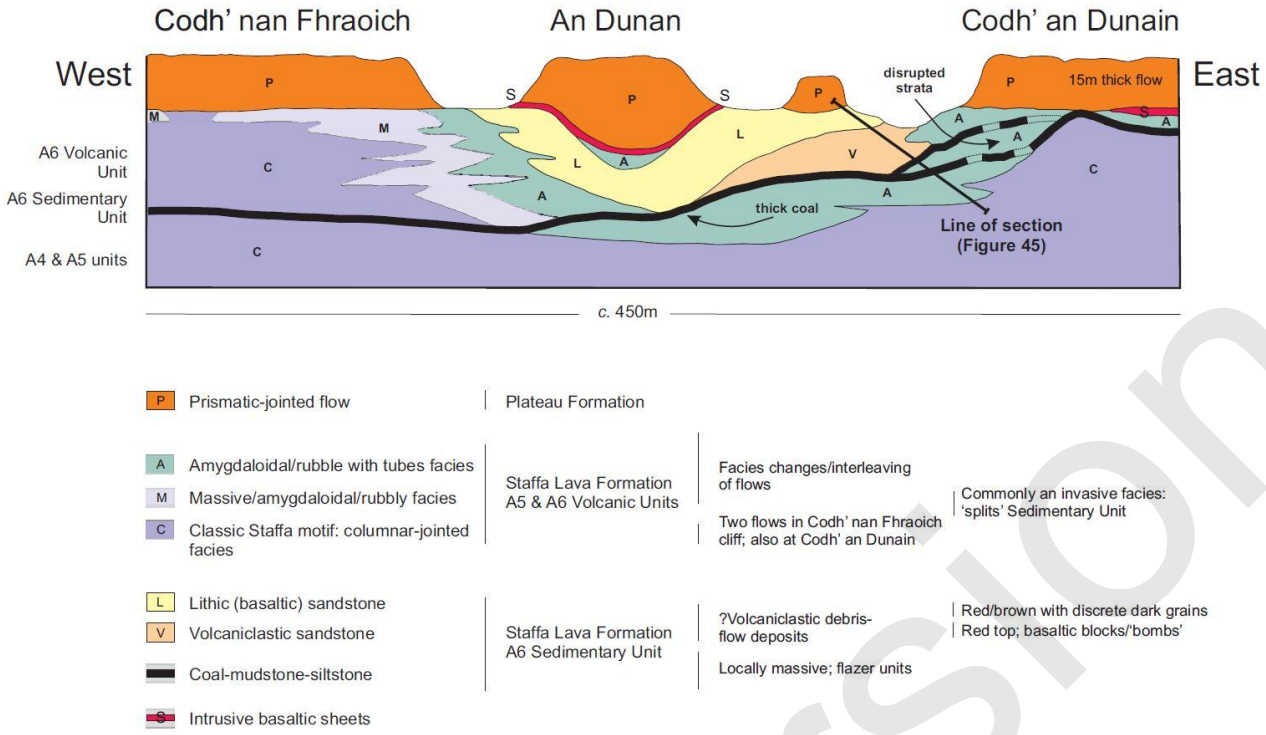


Figure 6-465: Schematic cross-section for the upper part of the sequence between Codh' nan Fhraoich and Codh'an Dùnain, south coast of Brolass (from Williamson & Bell 2012).

6.8.3 Mull Plateau Lava Formation: Mull

The most complete and relatively simplest succession of the Mull Plateau Lava Formation on Mull occurs at Ben More, where both the Ben More Main Member and the overlying Ben More Pale Member are present. This succession has been the subject of detailed geochemical examination (Kerr 1995a; Chambers & Fitton 2000; Chapter 10).

The Ben More Main Member occurs throughout west Mull, as well as on Morvern (Figure 6-466; Figure 6-467; Figure 6-468; Figure 6-469; Figure 6-470). Reddened, weathered tops to lavas, attributable to subaerial weathering, are relatively common, although interflow clastic sedimentary sequences have not been noted to any significant extent.

The member is composed of randomly interleaved olivine basalt and hawaiite lavas, together with rarer picrobasalt, mugearite, benmoreite and trachyte lavas. Certain lavas, especially the hawaiites and mugearites, are plagioclase macro-porphyritic (the Big Feldspar Basalts of Bailey *et al*. 1924).

Beta version



Figure 6-466: Ben More Main Member lavas, Ardmeanach, north side of Loch Scridain, west Mull.



Figure 6-467: Ben More Main Member lavas, north Gribun, west Mull.

Bold version



Figure 6-468: Ben More Main Member hawaiite and basalt lavas, north Ardmeanach, west Mull. Ian Williamson for scale.



Figure 6-469: Ben More Main Member basalt lavas, Caliach Point, NW Mull.



Figure 6-470: Ben More Main Member basalt lavas, Caliach Point, NW Mull.

Beta version

Some of the thin clastic beds within the lava-dominated sequence have been identified as ashy deposits, most likely reworked by stream action (Emeleus *et al.* 1996a). One easily accessed example crops out on the north side of Calgary Bay, NW Mull (Figure 6-471; Figure 6-472).



Figure 6-471: Reddened top to basaltic lava, overlain by pale thin silicic tuff, north side of Calgary Bay, NW Mull. Hammer *ca.* 30 cm long.



Figure 6-472: Detail of reddened top to basaltic lava, overlain by pale thin silicic tuff, north side of Calgary Bay, NW Mull. Knife *ca.* 10 cm long.

Little detailed information is available about the structure and stratigraphy of the Ben More Main Member. Below, two localities are briefly described in order to indicate some of the complexities and subtleties that are recognised.

The sequence of lavas that forms the coastal cliffs at Laggan Bay, near Ulva Ferry, banked up against, and eventually overstepped, a thick heterogeneous accumulation of basaltic ashes, volcaniclastic breccias and debris flow deposits (Figure 6-473; Figure 6-474). These clastic units most likely mark the site of a vent that penetrated the lava pile relatively early in the development of the Ben More Main Member. The majority of the clasts within the breccia are of basalt and hawaiite; however, rare but conspicuous angular fragments of Moine psammite and Turonian flint are identified, indicating that material from the subjacent crust has been transported upwards by the magma or eroded from surface outcrops.



Figure 6-473: Boulder conglomerate, with boulders and cobbles of basalt, hawaiite and mugearite, together with cobbles of Moine psammite and angular fragments of flint, in a sand-silt matrix, Laggan Bay, Loch Tuath, west Mull. Hammer *ca*. 30 cm long.

Be



Figure 6-474: Detail of boulder conglomerate, with boulders and cobbles of basalt, hawaiite and mugearite, together with cobbles of Moine psammite and angular fragments of flint, in a sand-silt matrix, Laggan Bay, Loch Tuath, west Mull. Hammer *ca.* 30 cm long.

On the west side of the Quinish peninsula, in NW Mull, a remarkably well-preserved lava crops out for a distance of at least 800 m along the coast between the high and low water lines (Figure 6-475; Figure 6-476; Figure 6-477). This lava preserves both casts (in basalt) and moulds of tree trunks and possibly branches, most of which are flat-lying, and the majority of which trend NE-SW. The upper portion of the underlying lava is severely lateritised, possibly representing the soil in which the trees grew. The surface features and internal structures that are preserved are more typical of lavas in active volcanic areas, for example, ropy pahoehoe structures, shell-like pahoehoe crusts, and basal or marginal breccias. The remarkable state of preservation of the lava and the presence of fossil trees are taken as a clear indication that the Quinish Lava erupted after a significant hiatus in the volcanic activity and was, itself, rapidly buried by the succeeding lava.

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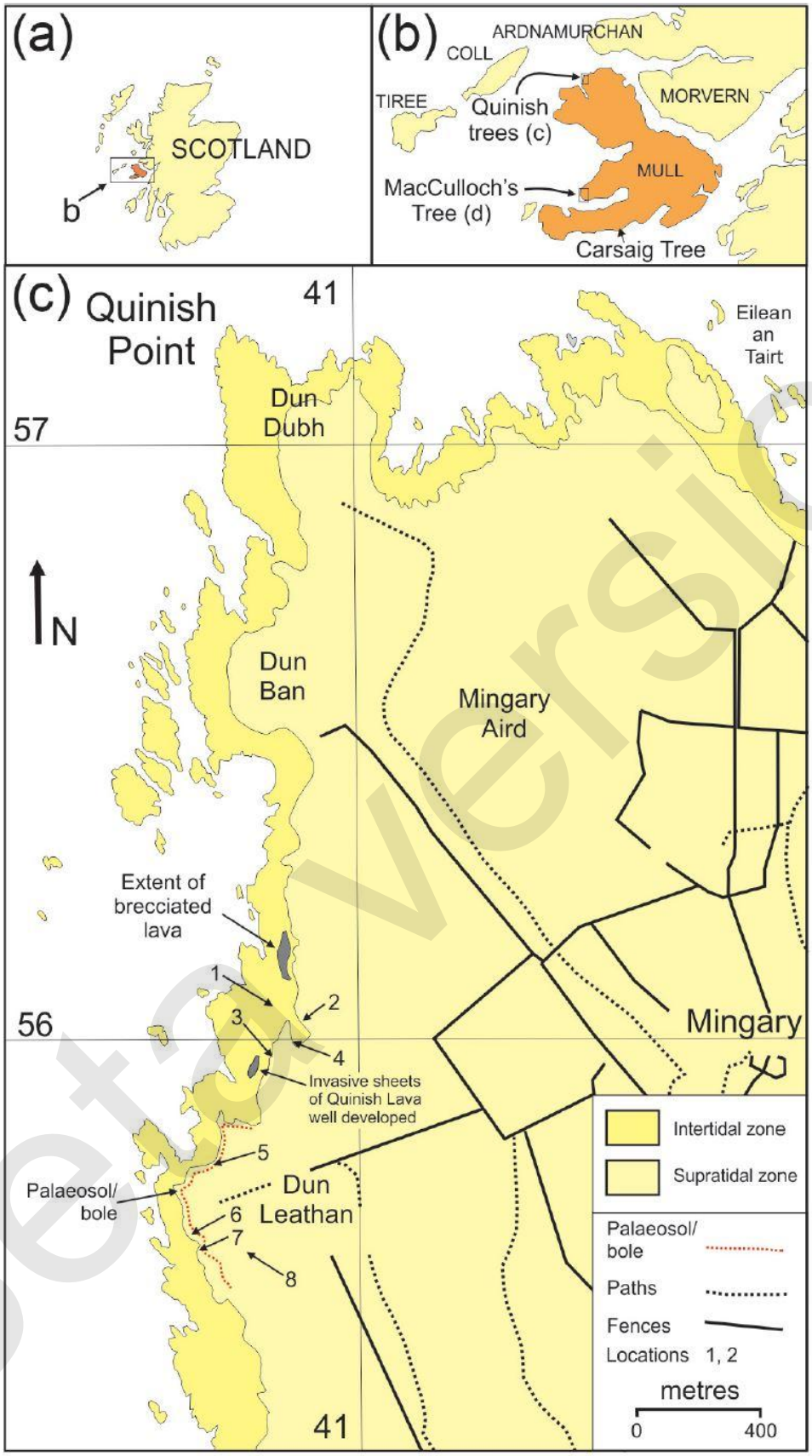


Figure 6-475: Location map for the fossil tree localities of the Quinish Lava, Quinish, NW Mull (from Bell & Williamson 2017).

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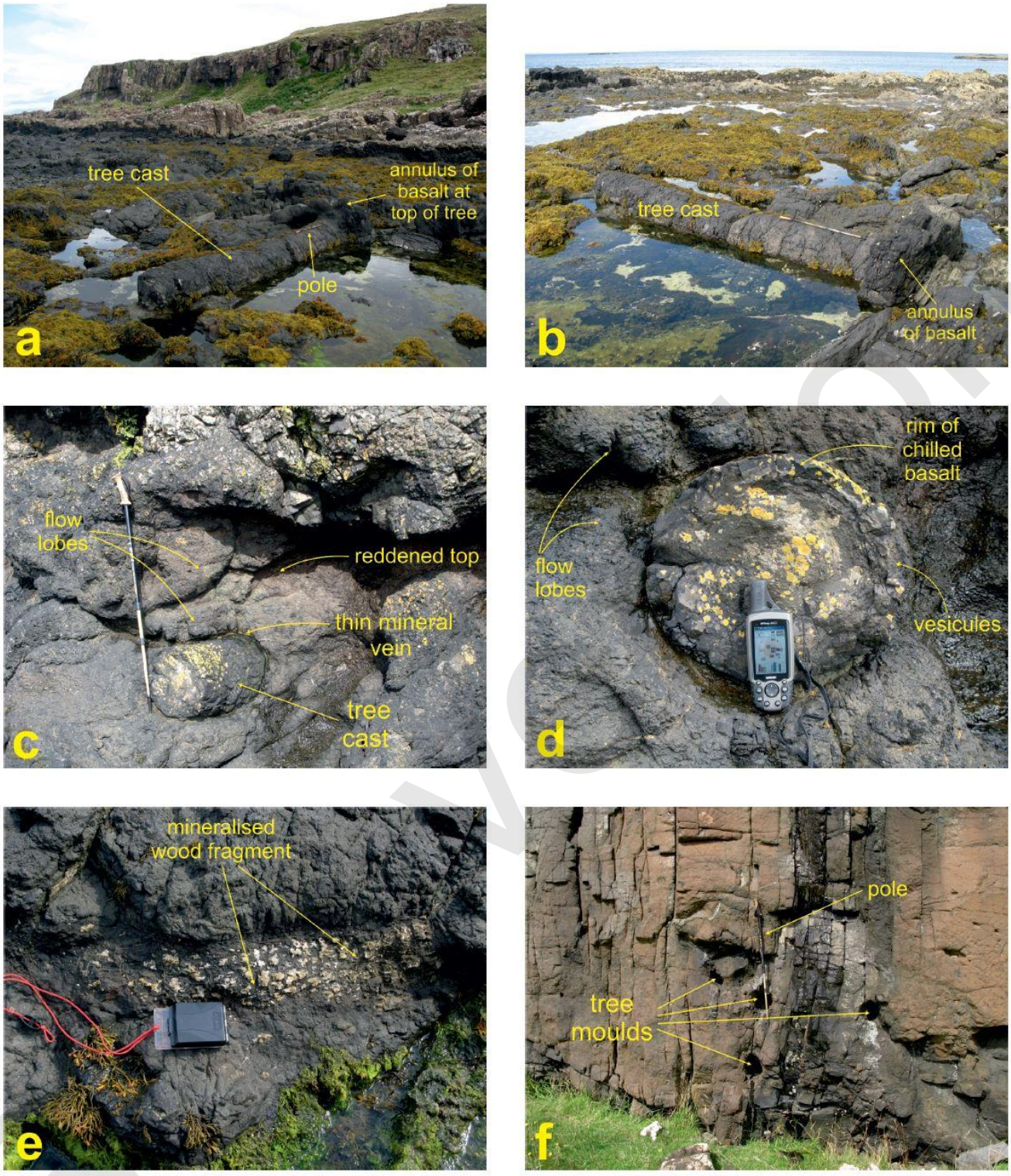


Figure 6-476: Fossil trees within the Quinish Lava, NW Mull: (a, b) prostrate cast of the main tree (Locality 1); (c, d) prostrate cast (Locality 2); (e) mineralised (calcite) wood fragment (Locality 3); (f) four prostrate moulds (Locality 8). Scales: pole (a, b, c, f) *ca.* 1 m long; GPS unit (d) *ca.* 15 cm long; compass (e) *ca.* 10 cm long. For figure locations, see Figure 6.430 (Bell & Williamson 2017).



Figure 6-477: Features of the Quinish Lava, NW Mull: (a) palaeosol below Quinish Lava at Dùn Leathan (between Localities 5 & 6); (b, c, d) internal features of the Quinish Lava; (e) subsurface invasive lava lobe within brecciated facies of the Quinish Lava; and, (f) breccia facies of the Quinish Lava. See Figure 6.430 for locations. Scale: pole *ca.* 1 m long (Bell & Williamson 2017).

The Ben More Pale Member crops out around the summit of Ben More, close to the western margin of the Mull Central Complex (Chapter 9) and, consequently, has been subjected to intense hydrothermal alteration and metasomatism (Figure 6-478; Figure 6-479; Figure 6-480; Figure 6-481). It overlies the Ben More Main Member, although no sharp boundary has been identified; rather, there is an interdigitation of lavas between the two members, over an interval of a few lavas, with the increasing preponderance of

pale-weathering lavas, up-sequence. The pale weathering lavas are generally of relatively evolved composition, typified by benmoreites (type locality, first identified by Tilley & Muir 1964). The lower part of the Ben More Pale Member consists predominantly of mugearite, benmoreite and trachyte lavas. The lavas with the most evolved compositions are recognisable in the field by their platy joints and a general fissility and occur in the middle part of the member. The uppermost part of the member marks a return to significantly less-evolved olivine basalt lavas (Kerr 1995a). Intercalated with the lavas are thin sedimentary deposits (Figure 6-482; Figure 6-483; Figure 6-484): on the north side of Ben More, a benmoreite lava is underlain by 30 to 60 cm of fissile black mudstone containing abundant fragments of benmoreite; and, a similar deposit at the same stratigraphical level occurs on the east side of A' Chioch. South of the summit of Ben More, Bailey *et al.* (1924) recorded *ca.* 3 m of brecciated black mudstone with plant remains overlying a mugearite lava.



Figure 6-478: Ben More Pale Member lavas, forming Ben More (left) and A' Chìoch (right), west-central Mull. View towards the NE.



Figure 6-479: Ben More Pale Member lavas, south side of Ben More, viewed from Maol nan Damh, west-central Mull.

Beta version



Figure 6-480: Ben More Pale Member lavas, A' Chìoch, west-central Mull. View towards the east from Ben More.



Figure 6-481: Ben More Pale Member lavas, north side of A' Chìoch, west-central Mull. View towards the east.

Beta version



Figure 6-482: Breccia, Am Binnein, between Loch Beag (at the eastern end of Loch Scridain) and Ben More, west-central Mull. Hammer shaft *ca*. 30 cm long.



Figure 6-483: Conglomerate, base of south cliff, Ben More, west-central Mull. Hammer shaft *ca*. 30 cm long.



Figure 6-484: Siltstone, base of south cliff, Ben More, west-central Mull. Compass *ca.* 10 cm long.

6.8.4 Mull Plateau Lava Formation: Morvern

The volcanic sequence on Morvern is *ca.* 400–500 m thick. Its stratigraphy is poorly documented and its correlation with the sequences on Mull and Ardnamurchan not known beyond formation level (Figure 6-485; Figure 6-486; Figure 6-487; Figure 6-488; Figure 6-489; Figure 6-490; Figure 6-491; Figure 6-492; Figure 6-493; Figure 6-494; Figure 6-495).



Figure 6-485: Basaltic lavas between Ardtornish Point and Inninmore Bay, forming the obvious terraced ground, SE (right-hand-side) of which are featureless Moine Supergroup psammites and pelites.

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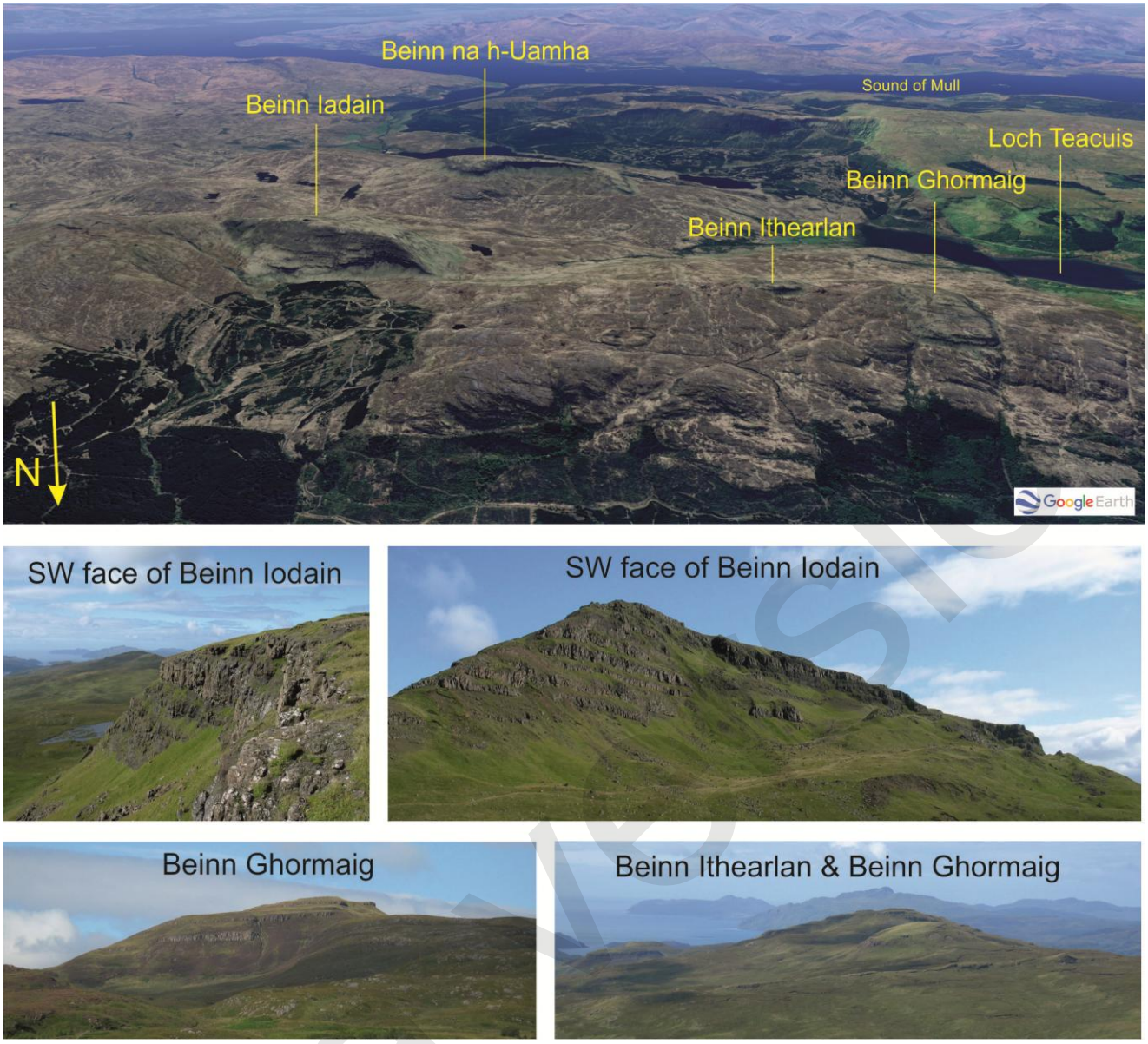


Figure 6-486: Annotated oblique Google Earth© image of outliers of the Paleocene lava sequence on Morvern and field views.



Figure 6-487: Outliers of the Paleocene lava sequence forming Beinn Iodain (left) and Beinn na h-Uamha (right), Morvern, viewed towards the SE from east of Ben Hiant, Ardnamurchan.

Beta Version



Figure 6-488: Paleocene volcanic sequence on the north side of Morvern, between Auliston Point and Torr nan Con. View towards south from Ardnamurchan.



Figure 6-489: Paleocene volcanic sequence on the north side of Morvern, east of Torr nan Con. View towards south from Ardnamurchan.



Figure 6-490: Late Proterozoic Moine Supergroup strata, locally overlain by Mesozoic strata, and unconformably overlain by prismatic-jointed basaltic lavas of the Paleocene volcanic sequence, Beinn Iodain, Morvern. People at base-volcanic unconformity for scale.

Browser version



Figure 6-491: Red lateritised top of a basaltic lava, south side of Beinn Iodain, Morvern. Hammer *ca*. 30 cm long.



Figure 6-492: Paleocene volcanic sequence, on Beinn Ithearlan, Morvern, view towards NW from Beinn Iodain towards Ben Hiant, Ardnamurchan.

Beta version



Figure 6-493: Paleocene volcanic sequence, SW face of Beinn Iodain, Morvern. View towards NW to Ben Hiant.



Figure 6-494: Paleocene volcanic sequence, Beinn Ghormaig, Morvern.

Beta version



Figure 6-495: Paleocene volcanic sequence, SW face of Beinn Iodain, Morvern.

6.8.5 Mull Plateau Lava Formation: Ardnamurchan

A small outcrop of the Mull Plateau Lava Formation occurs on Ardnamurchan. This outlier of the Mull Lava Field comprises thin basaltic lavas, commonly with reddened tops and best exposed on the roadside crags on the south side of Beinn Bhuidhe and on the NE side of Ben Hiant (Figure 6-496; Figure 6-497; Figure 6-498; Figure 6-499; Figure 6-500; Figure 6-501; Figure 6-502; Figure 6-503).



Figure 6-496: Angular unconformity with a flat-lying, jointed, orange-weathering basaltic lava, overlying a thin sedimentary unit (of Mesozoic age?), overlying pale, inclined Moine Supergroup psammites and pelites. Allt Torr na Moine, east of Ben Hiant, Ardnamurchan.

Pre-publication version



Figure 6-497: Terraced basaltic lavas on the south side of Beinne Buidhe, Ardnamurchan and, in the distance (left of centre), forming an obvious outlier on Beinn na h-Uamha, Morvern.



Figure 6-498: Terraced basaltic lavas on the south side of Beinne Buidhe, Ardnamurchan, and, in the distance, forming outliers on Beinn Iadain (left) and Beinn na h-Uamha (centre), Morvern.



Figure 6-499: Mid height terrace of basaltic lavas on the east side of Ben Hiant, Ardnamurchan, unconformably overlying poorly exposed Moine Supergroup strata, and with crags of dolerite forming the summit area.

Beta version



Figure 6-500: Terrace of basaltic lavas intruded by dolerite dykes on the east side of Ben Hiant, Ardnamurchan.



Figure 6-501: Detail of terrace of basaltic lavas, intruded by dolerite dykes, on the east side of Ben Hiant, Ardnamurchan.



Figure 6-502: Terrace of prismatic-jointed basaltic lavas on the east side of Ben Hiant, below the crags of Stallachan Dubha and Sròn Mhòr, Ardnamurchan.

Beta version



Figure 6-503: Terrace of prismatic-jointed basaltic lavas on the east side of Ben Hiant, Ardnamurchan.

6.8.6 Mull Plateau Lava Formation: Ardnamurchan breccias

The basaltic lavas on the NE side of Ben Hiant are overlain by a thick sequence of volcaniclastic strata interpreted previously as vent-filling pyroclastic agglomerates by Richey (1938) but subsequently reinterpreted as massive volcaniclastic conglomerates and breccias interbedded with siltstones and sandstones (Brown & Bell 2006, 2007a; Brown *et al*. 2009; BGS 2009, 2013). Outcrops of similar volcaniclastic strata occur on the north side of Ardnamurchan between Swordale Cave and Fascadale Bay but are complicated by intrusions of the Ardnamurchan Central Complex (Chapter 9). These clastic units were deposited by debris-flow, fluvial and lacustrine processes within a dissected landscape that developed on the earlier lava field in response to uplift accompanying the emplacement of the Ardnamurchan Central Complex.

Two members are recognised, the Ben Hiant Breccia Member (*ca*. 260 m thick) (Figure 6-504; Figure 6-505; Figure 6-506; Figure 6-507; Figure 6-508; Figure 6-509; Figure 6-510; Figure 6-511; Figure 6-512; Figure 6-513; Figure 6-514; Figure 6-515; Figure 6-516; Figure 6-517; Figure 6-518; Figure 6-519; Figure 6-520) and the Achateny Breccia Member (*ca*. 50-60 m thick) (Figure 6-521; Figure 6-522; Figure 6-523; Figure 6-524; Figure 6-525; Figure 6-526; Figure 6-527). Locally, the breccias contain clasts, including megablocks, of lava-field lithologies and Jurassic sandstone that could only have been transported during catastrophic mass-flow, gravity-driven events. Trachyte and rhyolite clasts indicate that relatively silicic volcanism also took place during the early stages of uplift.

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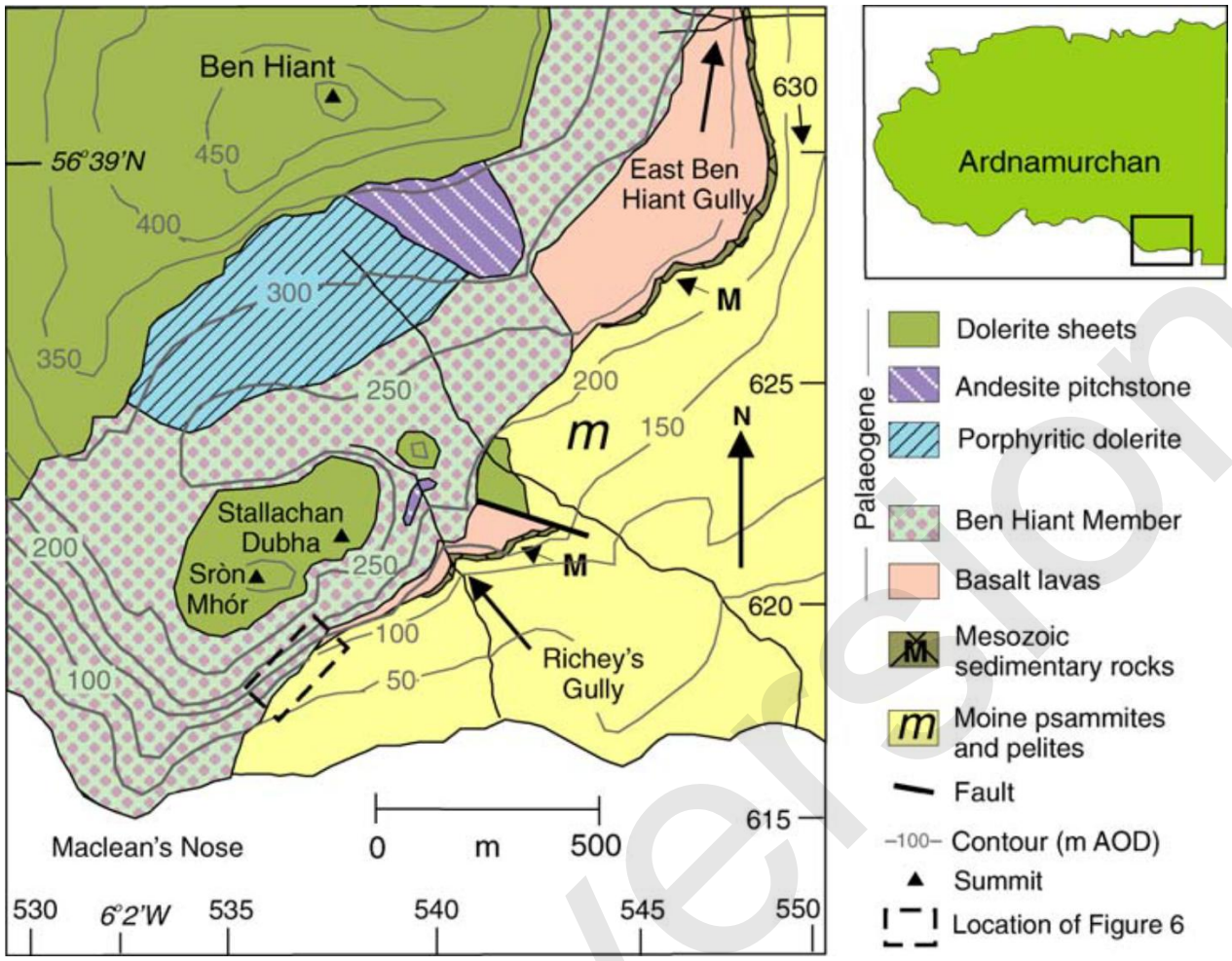


Figure 6-504: Simplified geological map of the Ben Hiant and Maclean's Nose area, Ardnamurchan (from Brown & Bell 2007).



Figure 6-505: SE side of Ben Hiant, Ardnamurchan, from Maclean's Nose to NE of the summit. At sea level, up to the obvious terrace at *ca.* 300 m, basement Moine Supergroup strata are dominant. The terrace is formed of flat-lying Paleocene basaltic lavas, with the ground above the terrace, up to the summit, dominated by dolerite intrusions. The bare rock cliff faces at Maclean's Nose are composed of coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member) overlying Moine Supergroup strata (psammites and pelites) and Paleocene basaltic lavas.

Beta version



Figure 6-506: SE side of Ben Hiant, Ardnamurchan. The bare rock cliff faces at Maclean's Nose are composed of coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member) overlying Moine Supergroup strata (psammites and pelites) and Paleocene basaltic lavas.

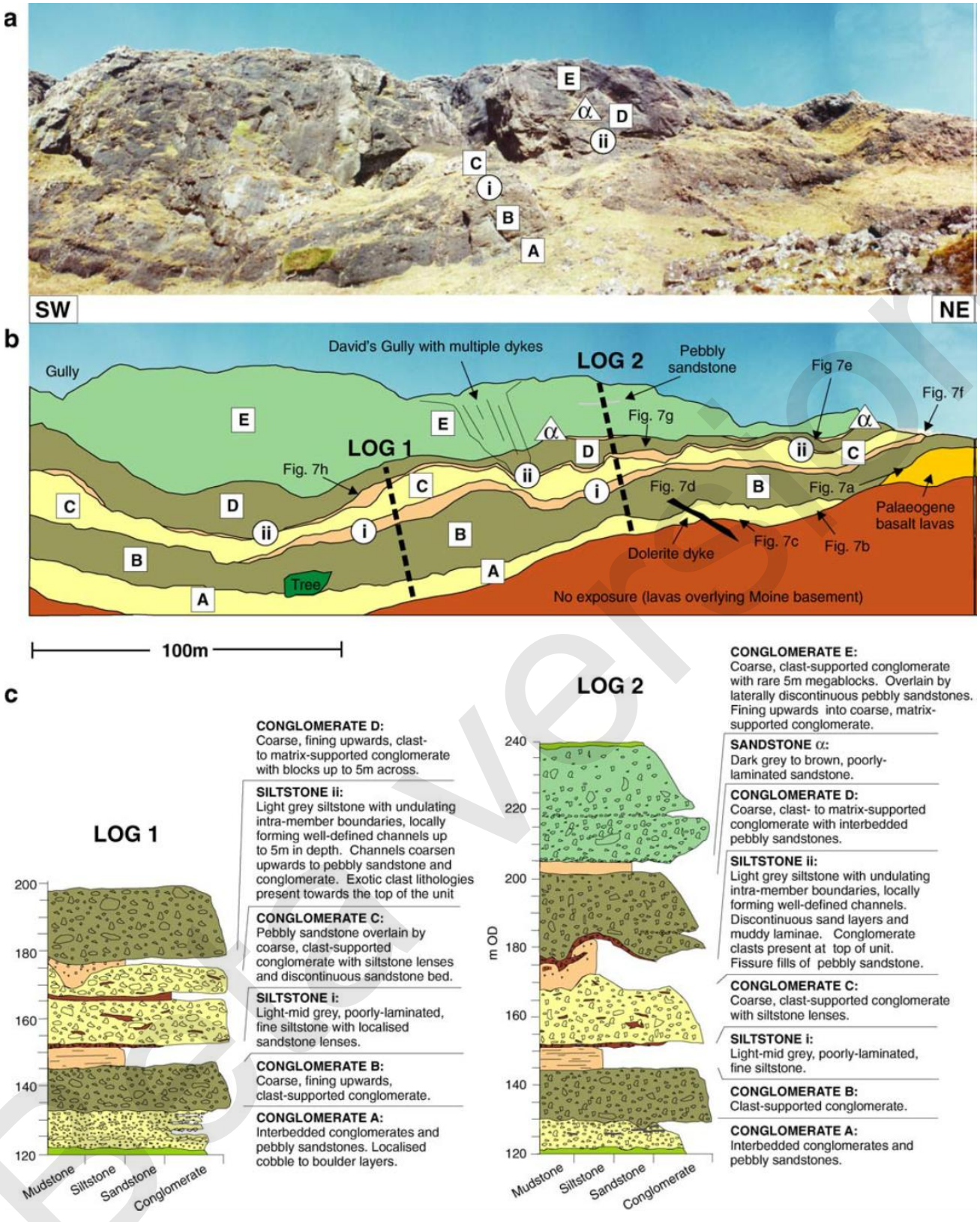


Figure 6-507: Photographic (a) and schematic (b) panoramas of the main Ben Hiant cliff section, together with two stratigraphic logs (c). The positions of Conglomerates A–E (in white squares), Siltstones i and ii (in white circles), Sandstone α (in white triangle), and the logs are indicated on the panoramas. Bedding relationships have been slightly distorted during the digital stitching process. Figure numbers detailed on figure are not included in this text (from Brown & Bell 2007).

Beta version



Figure 6-508: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member) overlying Moine Supergroup strata (psammites and pelites) (not seen), NE of Maclean's Nose, Ardnamurchan.



Figure 6-509: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member) overlying Moine Supergroup strata (psammites and pelites) (not seen), NE of Maclean's Nose, Ardnamurchan.



Figure 6-510: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan



Figure 6-511: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan.



Figure 6-512: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan. Thickness of section *ca*. 130 m.



Figure 6-513: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan.



Figure 6-514: Coarse Paleocene volcaniclastic deposits (Ben Hiant Breccia Member) overlying Paleocene basaltic lavas, NE of Maclean's Nose, Ardnamurchan.



Figure 6-515: Boulder-rich Paleocene volcaniclastic breccias and volcaniclastic sandstones and siltstones (at recess) (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan.



Figure 6-516: Boulder-rich Paleocene volcaniclastic breccias (Ben Hiant Breccia Member), NE of Maclean's Nose, Ardnamurchan. Hammer *ca*. 30 cm long.



Figure 6-517: Boulder-rich layer within Paleocene volcaniclastic breccias (Ben Hiant Breccia Member), close to top of section, Maclean's Nose, Ardnamurchan. Pole *ca*. 1 m long. Boulders are of plagioclase macro-porphyritic basalt/dolerite.



Figure 6-518: Detail of boulders of plagioclase macro-porphyritic basalt/dolerite within Paleocene volcaniclastic breccias (Ben Hiant Breccia Member), close to top of section, Maclean's Nose, Ardnamurchan. Pole *ca*. 1 m long.

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Figure 6-519: Boulder/block of ignimbrite (fabric approximately parallel to pole) within Paleocene volcaniclastic breccias (Ben Hiant Breccia Member), NE of Ben Hiant, Ardnamurchan. Pole *ca*. 1 m long.



Figure 6-520: Boulder-rich Paleocene volcaniclastic breccias (Ben Hiant Breccia Member), NE end of Ben Hiant ridge. Pole *ca*. 1 m long.

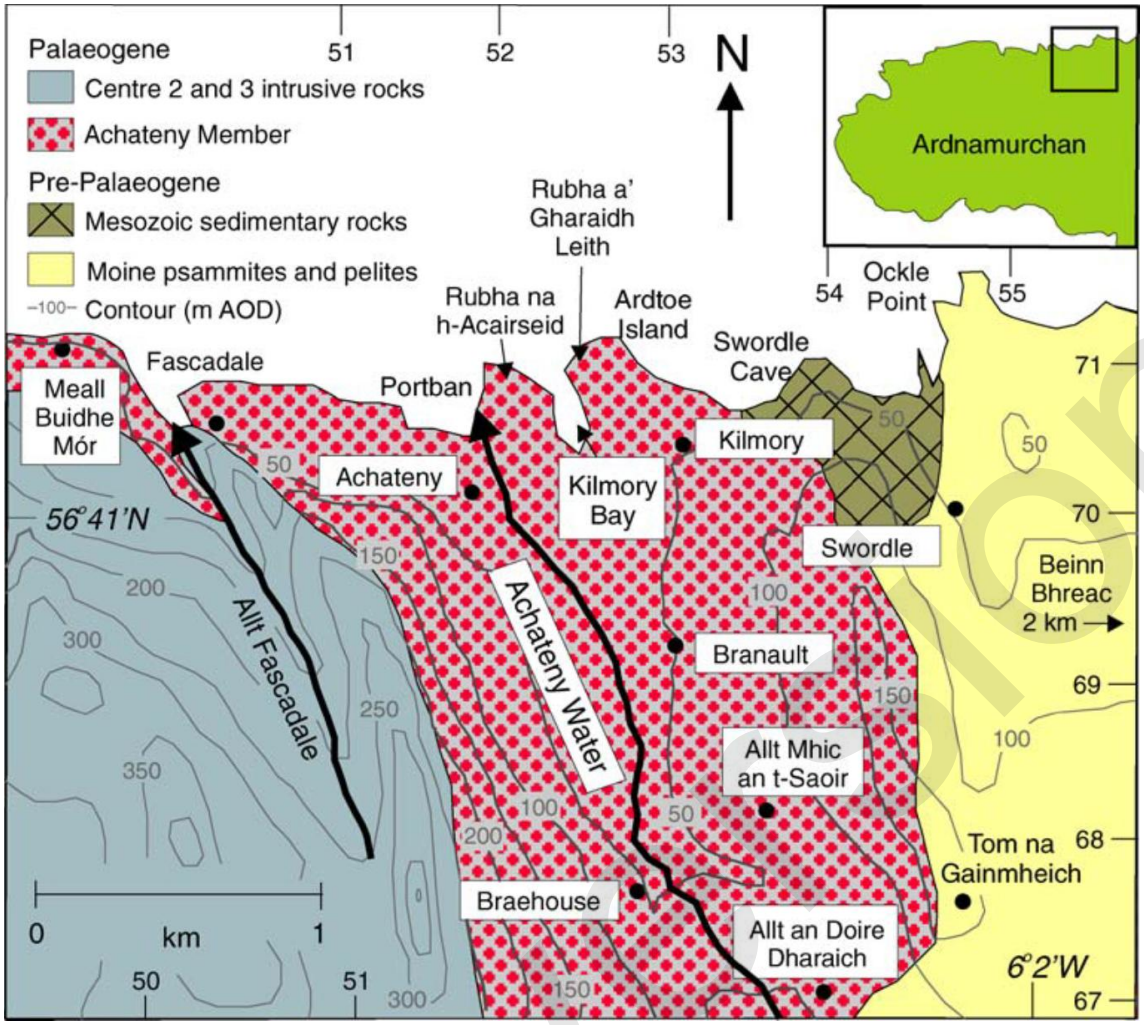


Figure 6-521: Simplified geological map of the Achateny area, north Ardnamurchan (from Brown & Bell 2007).



Figure 6-522: Mega-block of Jurassic calcareous sandstone within Paleocene volcaniclastic breccia (Achateny Breccia Member), Rubha na h-Acarseid, north Ardnamurchan. Person for scale.

Public Version



Figure 6-523: Boulder-rich Paleocene volcaniclastic breccia (Achateny Breccia Member), Kilmory, north Ardnamurchan, with blocks of Jurassic siltstone and sandstone in a fine-grained matrix. Pole *ca*. 1 m long.



Figure 6-524: Boulder-rich volcaniclastic breccia (Achateny Breccia Member), Kilmory, north Ardnamurchan, with blocks of Paleocene dolerite and Jurassic strata in a fine-grained matrix. Pole *ca*. 1 m long.



Figure 6-525: Boulder-rich volcaniclastic breccia (Achateny Breccia Member), Kilmory, north Ardnamurchan, with blocks of Paleocene dolerite and Jurassic strata in a fine-grained matrix. Pole *ca*. 1 m long.



Figure 6-526: Shale breccia (Achateny Breccia Member), Kilmory, north Ardnamurchan, with blocks of Jurassic shale in a fine-grained matrix. Pole *ca*. 1 m long.



Figure 6-527: Stratified Paleocene volcaniclastic sandstone within sequence of massive volcaniclastic breccias, Glendrian Caves, Rubha Carrach, north Ardnamurchan. Jeff Harris for scale.

Spatially associated with the Ben Hiant breccias are prismatic-jointed sheets of micro-porphyritic andesitic vitrophyre ('pitchstone'). Preservation of a localised and faint sheet-parallel fabric suggests a pyroclastic origin as ignimbrites (Brown *et al.* 2024). Five phases of eruption are recognised, producing deposits that range in character between non-welded and lava-like. The interval is assigned to a Sròn Mhòr Member, which unconformably overlies the clastic Ben Hiant Breccia Member (Figure 6-528; Figure 6-529).

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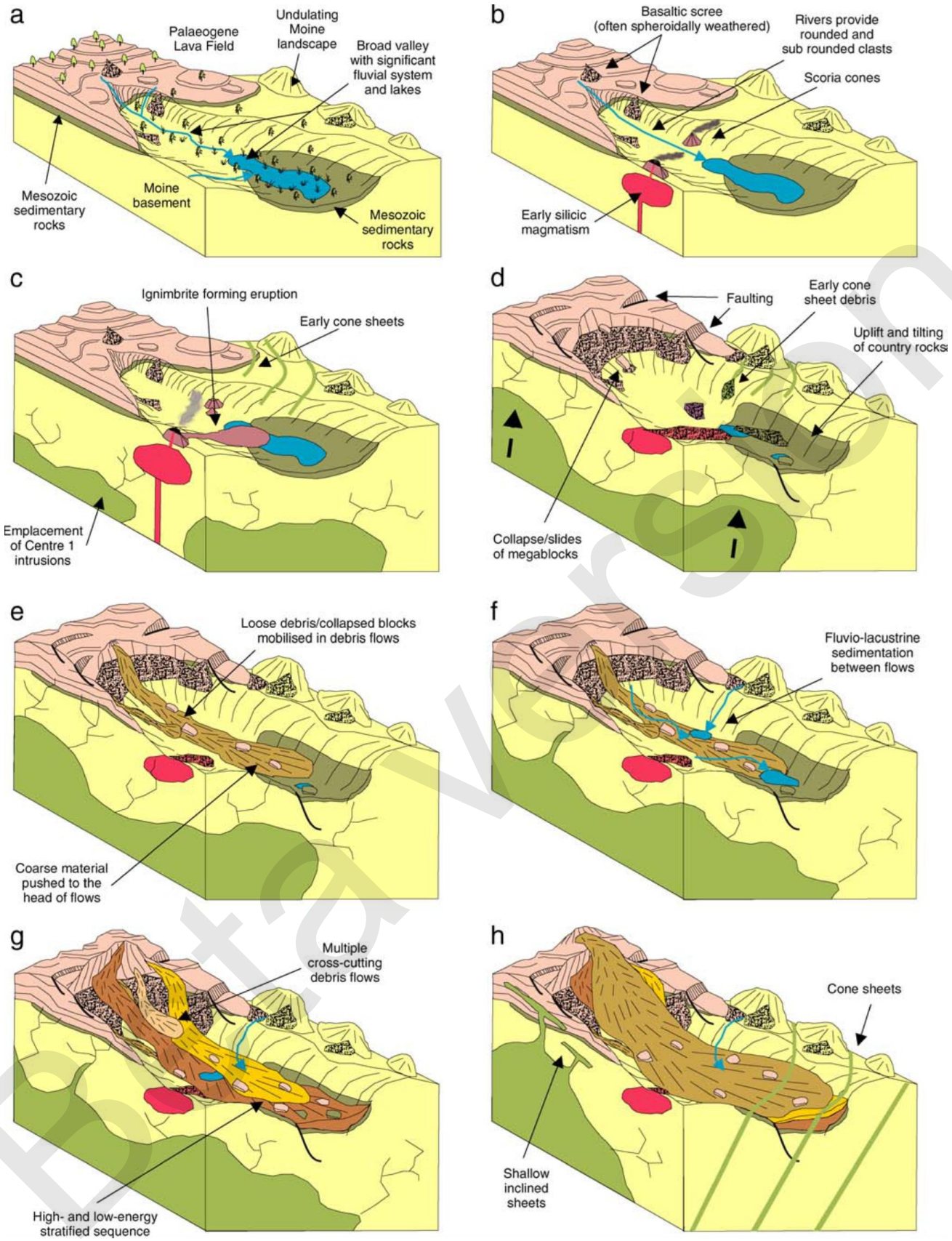


Figure 6-528: Crags of inclined, prismatic-jointed vitrophyre (ignimbrite) (Sròn Mhòr Member), at *ca.* 300 m OD, SE of summit of Ben Hiant, Ardnamurchan.



Figure 6-529: 'Nose' of prismatic-jointed vitrophyre (ignimbrite) (Sròn Mhòr Member), NE side of Richey's Gully, east of Stallachan Dubha, Ben Hiant, Ardnamurchan.

Brown & Bell (2007) present a diagrammatic reconstruction detailing the key events in the formation of the clastic sequences of the Ben Hiant and Achateny members (Figure 6-530).



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Figure 6-530: Schematic reconstruction of the uplift, erosion and sedimentation history of the Ardnamurchan breccias/conglomerates (from Brown & Bell 2007). This reconstruction is a generalised interpretation of events in the Ardnamurchan district and depicts an amalgamation of features observed in the Ben Hiant and Achateny members. One flank of the postulated sedimentary watershed is illustrated, but similar events would have occurred on the opposing side. (a) Early Paleocene landscape with upland forested areas, draining into lowland areas characterised by heavily vegetated swamps and lake environments. Erosion locally exposed Mesozoic sedimentary rocks and Late Proterozoic (Moine Supergroup) basement, producing scree/talus deposits; (b) early silicic and basic magmatism of the Ardnamurchan Central Complex (ACC) produced minor intrusions, locally forming small vents and cones. Fluvial systems deposited sub-rounded and rounded clasts on valley floor and slopes; (c) ignimbrite-forming eruptions occurred. Basaltic magma of the ACC was emplaced into the country-rocks and some intrusions reached shallow crustal levels; (d) early silicic intrusions were unroofed and eroded. Continued emplacement of the ACC caused uplift and doming of the Ardnamurchan district. Faulting detached mega-blocks from the land surface, which collapsed/slid downslope; (e) detritus was mobilised in debris flows, which entrained weathered and eroded material from the land surface. The largest clasts were pushed to the front of flows; (f) flows began to wane, forming hyperconcentrated and streamflow deposits. Small rivers and lakes formed during the more quiescent periods; (g) further uplift of the ACC continued, initiating multiphase debris flow deposition, and preserving a high- and low energy stratified sequence; (h) debris flow conglomerates were cut by later intrusions of the ACC. In this interpretation, the andesitic ignimbrites of the Sròn Mhòr Member (see above), would post-date the debris flow deposits.

6.8.7 Mull Central Lava Formation

The Mull Central Lava Formation consists of tholeiitic basalt lavas that crop out in small areas within the Mull Central Complex (Chapter 9) and possibly around its margins, where they overlie the Mull Plateau Lava Formation (Bailey *et al.* 1924) (Figure 6-531). The formation is *ca.* 900 m thick, and many of the lavas may have been erupted within a water-filled caldera, forming a thick succession of pillowed flows (Bailey *et al.* 1924). This is the SE Caldera or Early Caldera of Bailey *et al.* (1924); the structure is *ca.* 10 km in diameter and is thought to have developed as a consequence of the summit collapse of a central vent volcano on a site now occupied by the Mull Central Complex. Subsequent intrusive activity within the central complex has dismembered the lavas. Another, younger, caldera is recognised, the so-called NW Caldera (Bailey *et al.* 1924), although lavas of the Mull Central Lava Formation within this structure are not pillowed. Throughout the formation, intense hydrothermal alteration has led to severe changes to the primary mineralogy of many of the lavas, with the development of abundant secondary epidote and prehnite, commonly replacing primary minerals, but also in fracture-filling vein systems.

Within the putative SE Caldera, Bailey *et al.* (1924) recognise three zones within the formation, although complications due to subsequent structural and intrusive events prevent the thicknesses of these zones being defined. Pillowed lavas are restricted to the Outer Zone and the Middle Zone. Based on the significant thicknesses of pillow lavas still preserved, Bailey *et al.* (1924) argue that there must have been successive subsidence events of the caldera floor.

It is important to note that these lavas, of distinctive tholeiitic basalt composition, were not always contained within the caldera. It is speculated that some were able to flow outwards, presumably down the flanks of the volcanic superstructure, and possibly to interdigitate with flows of the Mull Plateau Lava Formation that had been erupted from fissure systems.

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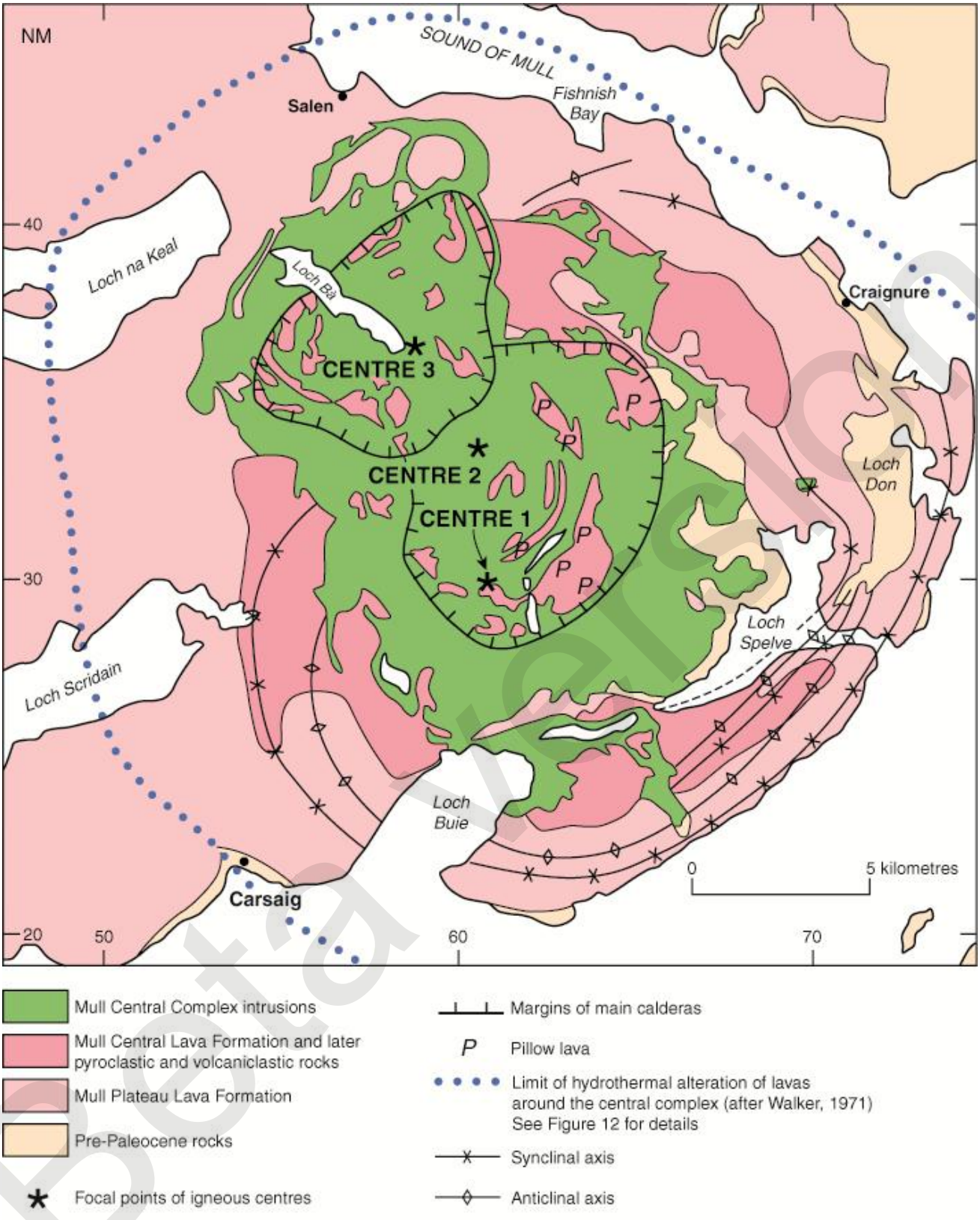
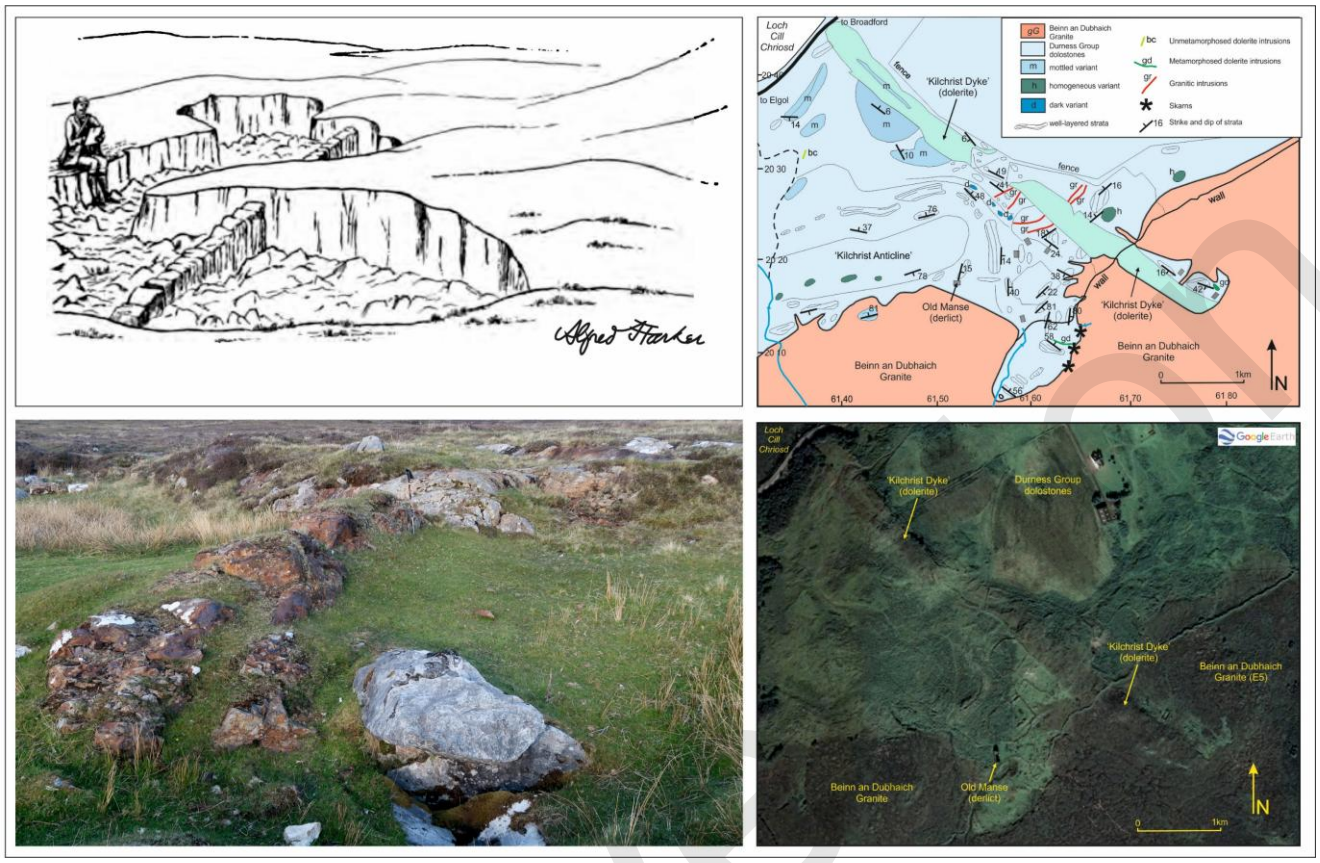


Figure 6-531: Putative caldera locations associated with the Mull Central Complex (after Emeleus & Bell 2005).

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7 Dykes, dyke swarms and volcanic plugs



Basaltic dykes intruded by the (younger) Beinn an Dubhaich Granite, Strath, Skye

7.1 Introduction and general field characteristics

Dykes of Paleocene age are present throughout western Scotland and the Hebrides and commonly occur in parallel, NW-SE to NNW-SSE -trending regional swarms, becoming more numerous and varied in direction near to and within the central complexes (Figure 7-1) (Speight *et al.* 1982). Volcanic plugs are much less common and occur principally within or close to the lava fields and central complexes.

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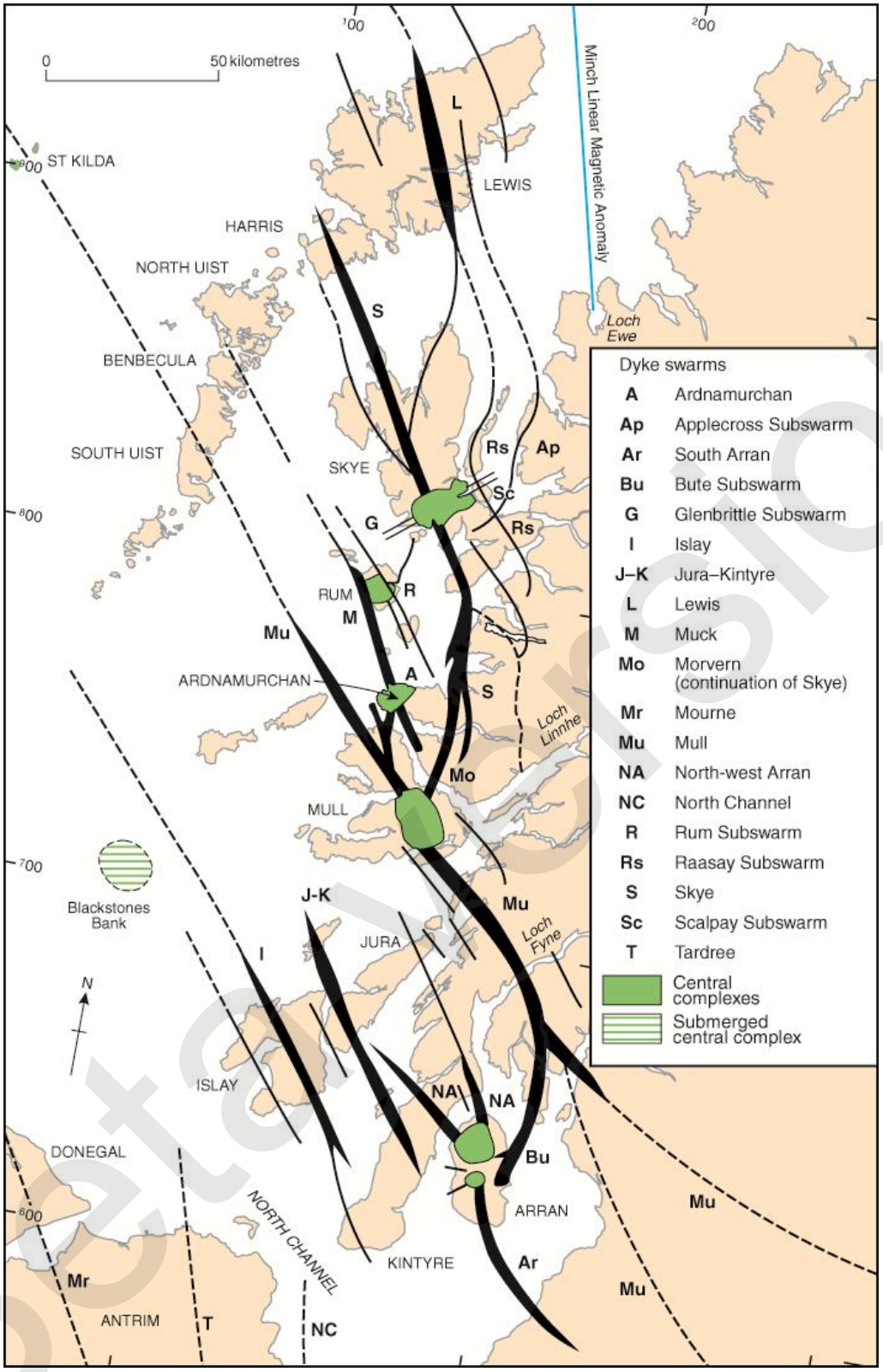


Figure 7-1: Dilation axes of the Paleocene dyke swarms in the Hebridean area. Broader lines indicate the main axes of the regional swarms; broken lines indicate less certain axes (after Speight *et al.* 1982). The Minch Linear Magnetic Anomaly is also interpreted as a dyke or dyke swarm

Although most of the dykes are a metre or less in width, intrusions between 2 and 10 m are not uncommon, and thicker examples are known (Figure 7-2; Figure 7-3; Figure 7-4; Figure 7-5).

Beta Version



Figure 7-2: Wide multiple dolerite dykes on west side of the Allt Camas Fhionnairigh, Camasunary, central-south Skye.



Figure 7-3: Wide plagioclase porphyritic dolerite dyke, Am Màm, Strathaird, central-south Skye. Iain Allison for scale.

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Figure 7-4: Wide, prismatic-jointed dolerite dyke, Rubha an Dunain, Loch Brittle, SW of the Cuillin, Skye.



Figure 7-5: Dolerite dyke cutting Middle Jurassic Druim an Fhuarain Sandstone Member of the Bearreraig Sandstone Formation sandstone, south of Elgol, Strathaird, Skye. Iain Allison for scale.

On Skye, there is evidence that larger dykes may be built up incrementally by numerous small injections of magma (Platten 2000). Examples of narrow dykes that cut and chill against each other and against a spatially and temporally associated larger dyke and its country-rock are common (Figure 7-6; Figure 7-7;

Figure 7-8**)**. In each instance, the narrow dykes can be traced into the larger dyke for only a short distance, where they terminate. In some cases, at these terminations, the central parts of both dykes merge and the chilled margin is absent. Platten (2000) concluded that after the initial dilation of a fracture and the introduction of magma, there were subsequent increments of dilation, sufficiently spaced in time for preceding injected batches of magma to have solidified (crystallised). Distant from the dyke terminations, the dyke fissure was maintained as an open, magma-filled void due to continued flow of magma during further increments of fracture dilation. From these observations, it is concluded that magma-filled dyke fissures varied in width during their development, possibly controlled by magma input pressure.



Figure 7-6: Field images of dykes from Coire Làgan (Cuillin, Skye) exposures, SW of the unnamed lochan, intruded into Outer Bytownite Troctolites: (a) apparent basalt dyke terminations, pole *ca*. 1 m long; and, (b) dolerite dyke offset, coin *ca*. 24 mm across.

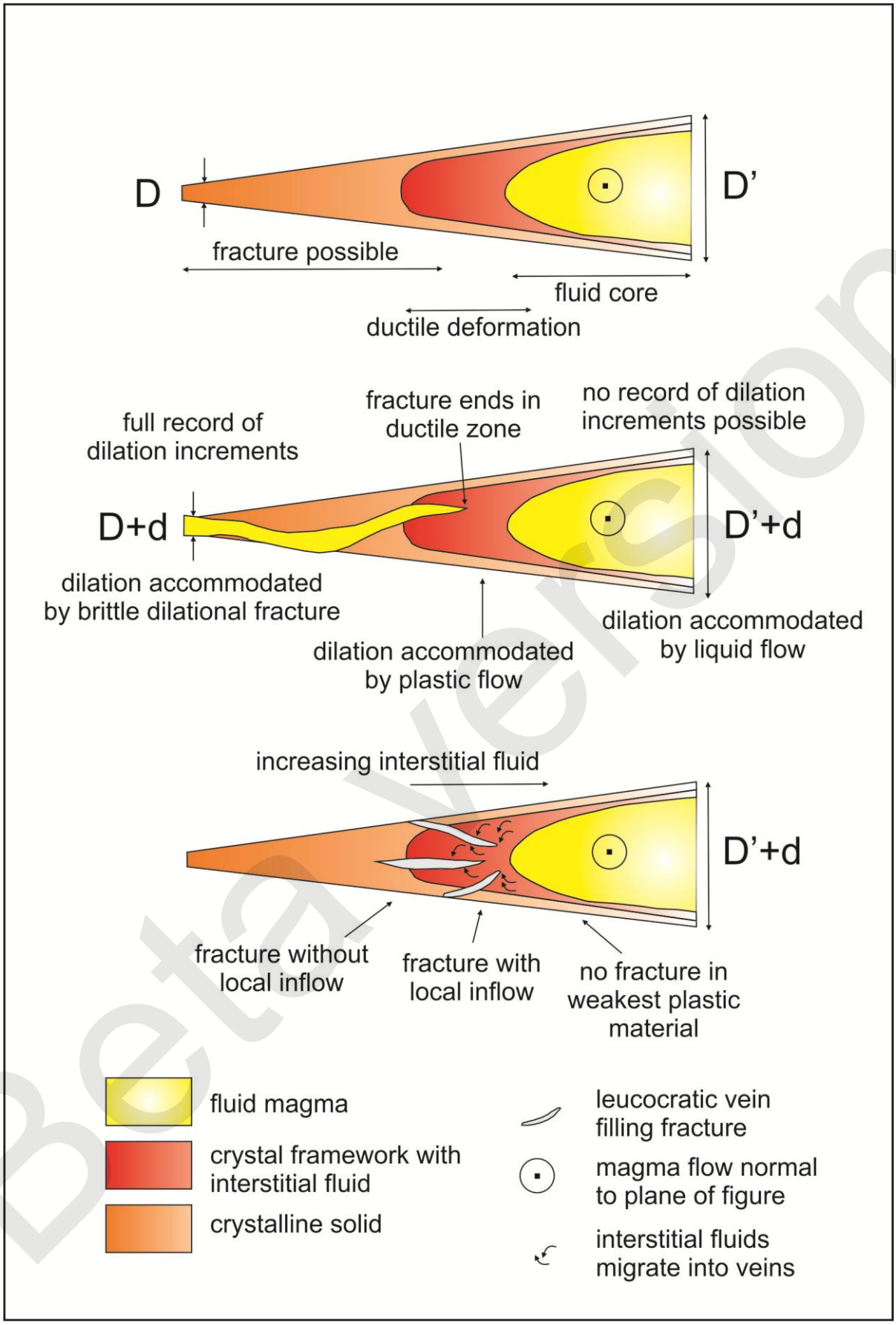


Figure 7-7: The effects of incremental dilation during dyke emplacement (after Platten 2000).

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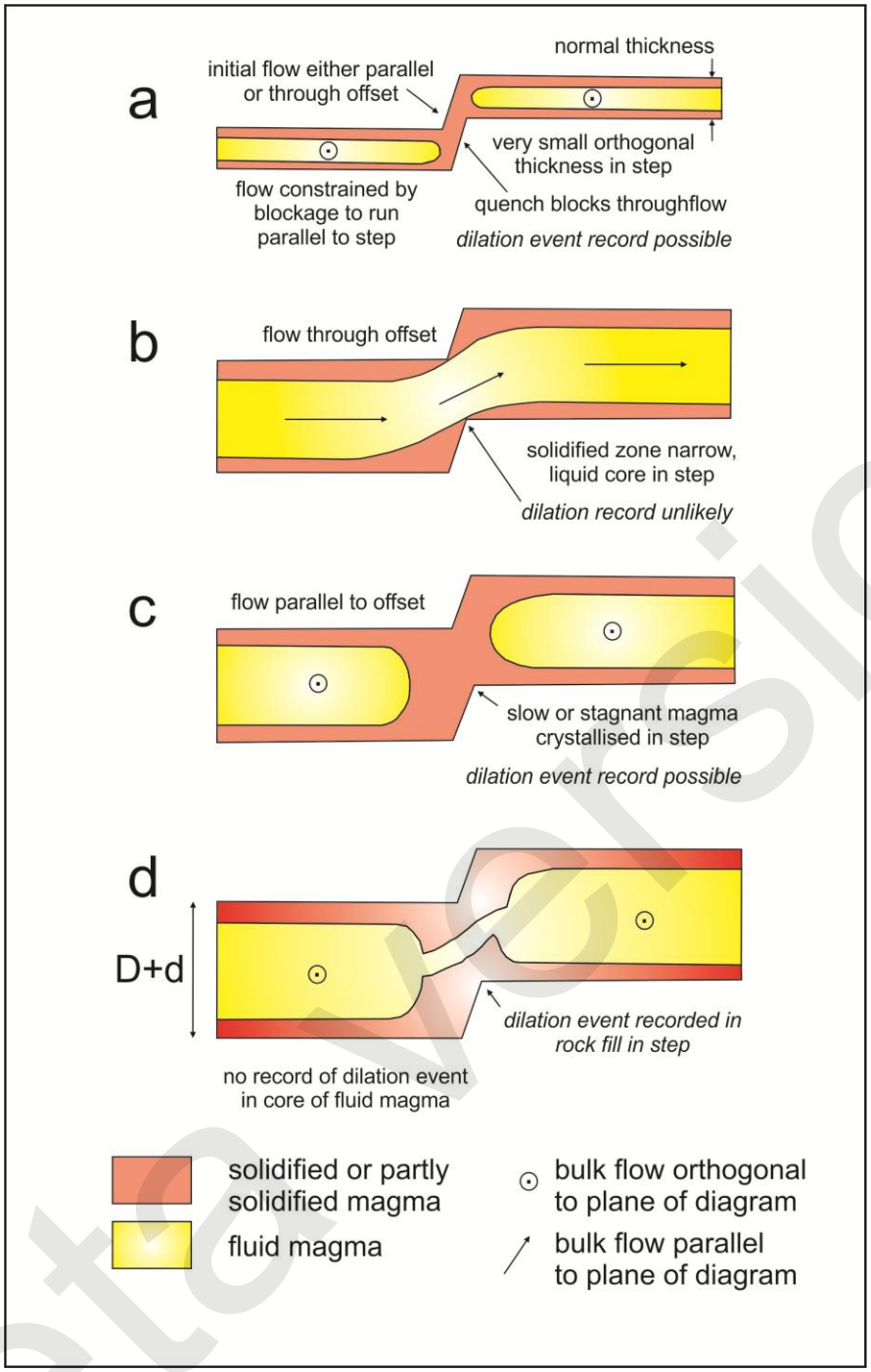


Figure 7-8: Dyke emplacement processes (after Platten 2000).

The pronounced Minch Magnetic Anomaly to the east of the Isle of Lewis has been attributed to a dyke that averages *ca*.1.1 km in thickness (Ofoegbu & Bott 1985; Fyfe *et al*. 1993) but no outcrop occurs onshore. A notable example of an unusually thick dyke, up to 100 m in width, crosses Muck in several *en échelon* outcrops (Figure 7-9). This dyke consists of olivine-gabbro and olivine-dolerite, and the gabbroic facies has developed small-scale mineral layering, similar to layering in the sills of north Skye. Paleocene lavas and sedimentary rocks of Mid Jurassic age intruded by the Muck dyke are altered to high-temperature, Sanidinite-Facies hornfelses (Emeleus 1997). The Muck dyke most likely acted as a feeder for lava flows; prolonged passage of magma, maintaining high temperatures, is inferred from the intense thermal alteration of the host rocks. In general, however, the Hebridean dykes produced only slight induration and thermal metamorphism of the immediately adjoining host rocks.

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Figure 7-9: The Muck (Camas Mòr) dyke, south coast of Muck.

The dykes in and near the central complexes are generally less than 2 m in thickness. However, injection of dykes side by side into the same fissure can result in thick multiple intrusions, which are most common close to the central complexes (Figure 7-10; Figure 7-11; Figure 7-12). On Strathaird, to the SE of the Cuillin Intrusive Centre, *ca*. 60% of the dykes in the Skye Regional Dyke Swarm are multiple; large numbers of multiple dykes also occur close to the Mull Central Complex.



Figure 7-10: Multiple dolerite dyke, intruded into Middle Jurassic strata, west coast of Strathaird, Skye.

Beta version



Figure 7-11: Multiple dolerite dyke intruded into Pabay Shale Formation strata on the north side of Loch Eishort, Strath. Iain Allison for scale.



Figure 7-12: Multiple dolerite dykes intruded into hornfelsed basaltic lavas in abandoned quarry at the head of Loch Sligachan, Skye. Pole *ca*. 1 m long.

Multiple dykes crop out along the south coasts of Arran and Muck and, due to differential weathering and erosion, stand proud of the softer and more easily eroded country-rocks (Figure 7-13; Figure 7-14; Figure 7-15**).**



Figure 7-13: Multiple dolerite dykes, intruded into Triassic strata, south coast of Arran.



Figure 7-14: Multiple dolerite dykes, intruded into Triassic strata, south coast of Arran.

Beta version



Figure 7-15: Multiple dolerite dykes, intruded into Jurassic strata, Camas Mòr, south coast of Muck.

Composite dykes, in which magmas of contrasting composition have been intruded in quick succession, generally without internal chilling, are less common and are also usually restricted to the vicinity of central complexes. On Arran, good examples of composite dykes, some vitrophyres, crop out on the Tormore shore section (Figure 7-16; Figure 7-17; Figure 7-18), north of the composite Drumadoon Sill (Chapter 8). At these localities, initial intrusion of quartz-dolerite magma has been followed in rapid succession by quartz-feldspar porphyry or (silicic) vitrophyre magma injected into the centre of the dyke.



Figure 7-16: Dolerite dyke (right-of-centre, bottom) and quartz-feldspar porphyry/vitrophyre dyke (bottom-right), Tormore, west coast Arran.

Beta version



Figure 7-17: Quartz-feldspar porphyry/vitrophyre dyke, Tormore, west coast Arran. Coin *ca.* 24 mm across.



Figure 7-18: Vitrophyre dyke, Tormore, west coast Arran. Pole *ca.* 1 m long.

Dykes generally have chilled, fine-grained margins against their host rocks (Figure 7-19; Figure 7-20). Glassy selvedges are rare in basaltic dykes, but at Camas na Cairdh, Muck, dark, vitreous tachylyte occurs

on the margins of several dolerite dykes and flow-structures in the glass indicate that locally the magma moved nearly horizontally through the dyke fissure.

Many of the dykes intruded into the Coire Dubh breccias on Rum (Chapter 9) have well developed and obvious chilled margins (Figure 7-21; Figure 7-22; Figure 7-23; Figure 7-22; Figure 7-23).

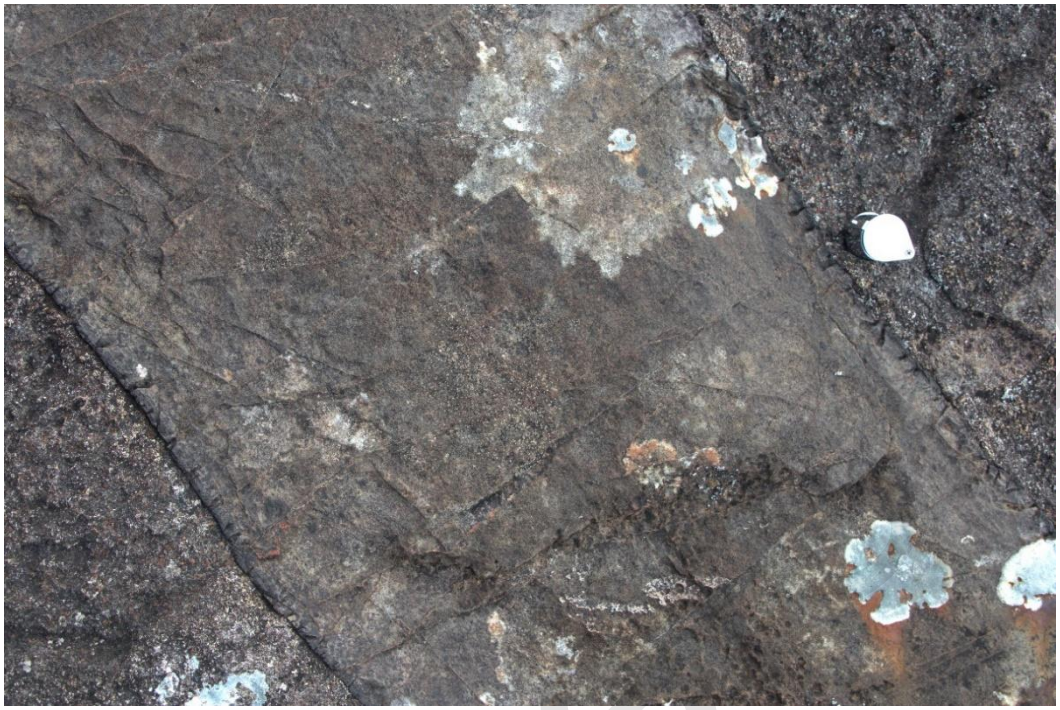


Figure 7-19: Glassy margin of dolerite dyke with chill-induced fracture development. Hand lens *ca*.6 cm long.



Figure 7-20: Detail of glassy margin of dolerite dyke with chill-induced fracture development. Hand lens *ca*.6 cm long.



Figure 7-21: Dolerite dyke with internal (flow alignment) fabric and chilled (glassy) margin, Coire Dubh, Rum. Hammer *ca.* 30 cm long.



Figure 7-22: Dolerite dyke with internal (flow alignment) fabric and chilled (glassy) margin, Coire Dubh, Rum. Hammer *ca.* 30 cm long.



Figure 7-23: Cross-cutting dykes with chilled margins, Coire Dubh, Rum. Hammer *ca.* 30 cm long.

Where basalt (and dolerite) dykes occur within carbonate-rich sedimentary rocks, especially shales, subsequent alteration of the dyke by hydrothermal fluids can occur (Figure 7-24; Figure 7-25).



Figure 7-24: Thin basaltic dyke with altered margins within Middle Jurassic shales, west side of Camas Mòr, south Muck.



Figure 7-25: Thin basaltic dyke with altered margins within Lower Jurassic sandstones, Craignure, SW Mull. Poles *ca*. 1 m long. [Photograph courtesy of James Westland]

Wholly or largely glassy silicic dykes are, by contrast, comparatively common. Classic examples occur at Tormore on the west coast of Arran, where dark green, flow-banded (silicic) vitrophyres (or glassy 'pitchstones' of older literature) have intruded Triassic sandstones (Figure 7-26).



Figure 7-26: Flow-banded vitrophyre (or glassy 'pitchstone' of older literature) dyke, Tormore, west coast Arran, Coin *ca*. 24 mm across.

The commonest internal structures in basaltic dykes are planar zones of amygdales parallel to the dyke margins. Less common are oriented phenocrysts, most commonly plagioclase, in basaltic dykes (Figure 7-27; Figure 7-28).

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Figure 7-27: Plagioclase porphyritic dyke, west coast of Strathaird, Skye. Pole *ca.* 1 m long.

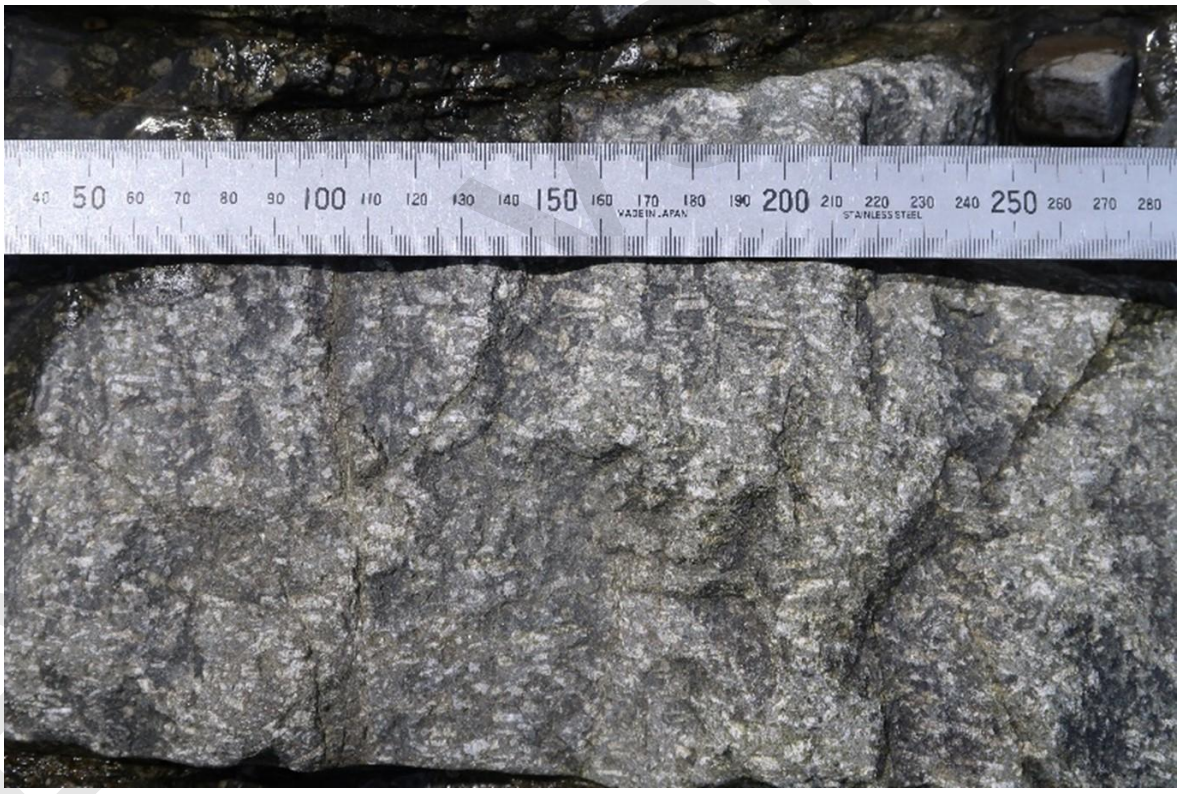


Figure 7-28: Detail of aligned plagioclase phenocrysts in porphyritic dyke, west coast of Strathaird, Skye. Ruler for scale.

Rarely, there is also internal textural variation parallel to the dyke walls, for example a dolerite dyke on Trotternish, Skye, emplaced within a picrite sill (Figure 7-29).

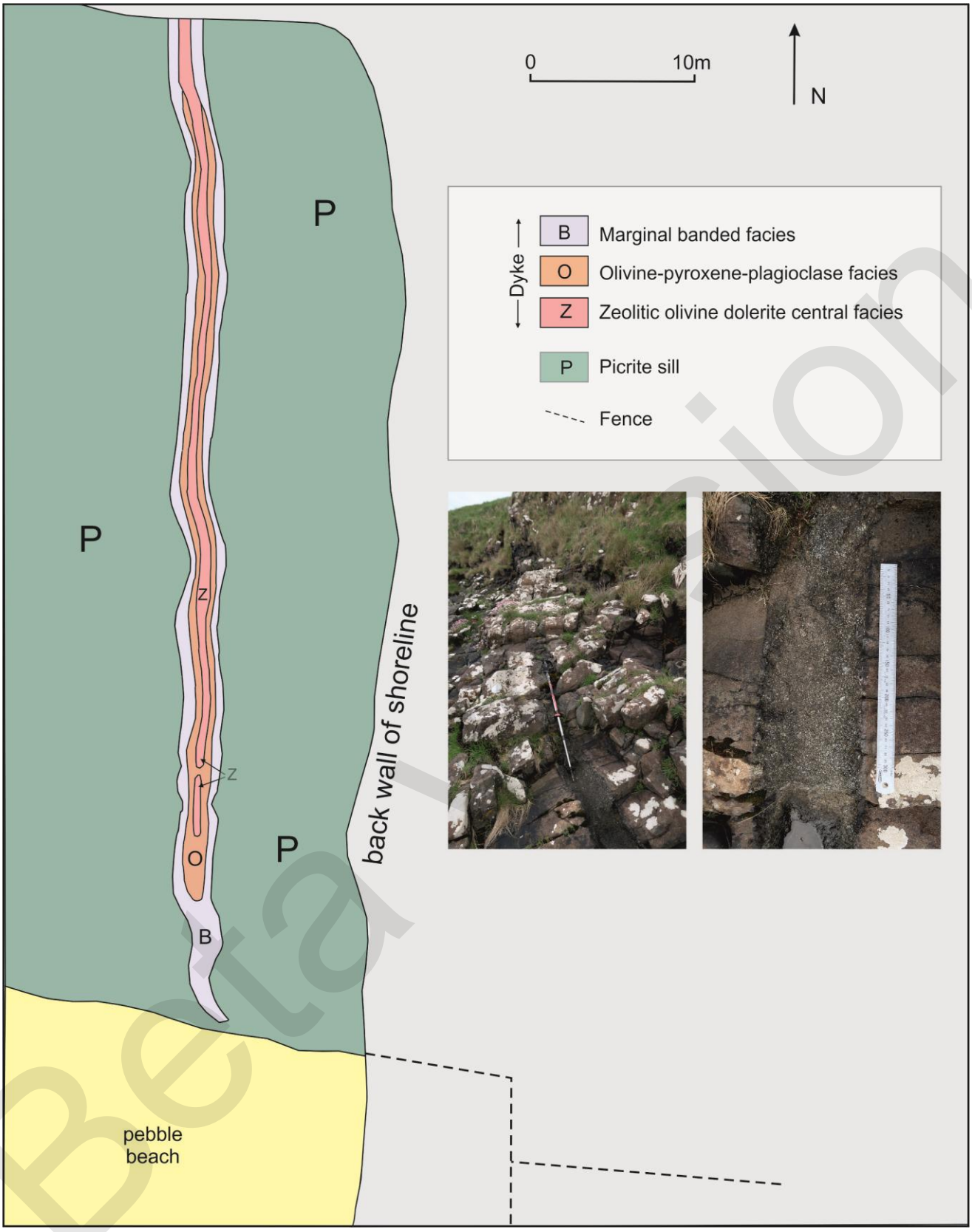


Figure 7-29: Composite dolerite dyke with internal textural variation parallel to margin of intrusion, Bornesketaig, NW Trotternish, Skye. Pole *ca.* 1 m long; ruler 30 cm long.

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Stratification, or layering, is rare, with one well exposed example on the east shore of Loch Slapin at Suisnish, Skye, where a picrite dyke has mineralogy-specific layers, further emphasised by the presence of cognate xenoliths (Figure 7-30; Figure 7-31; Figure 7-32).

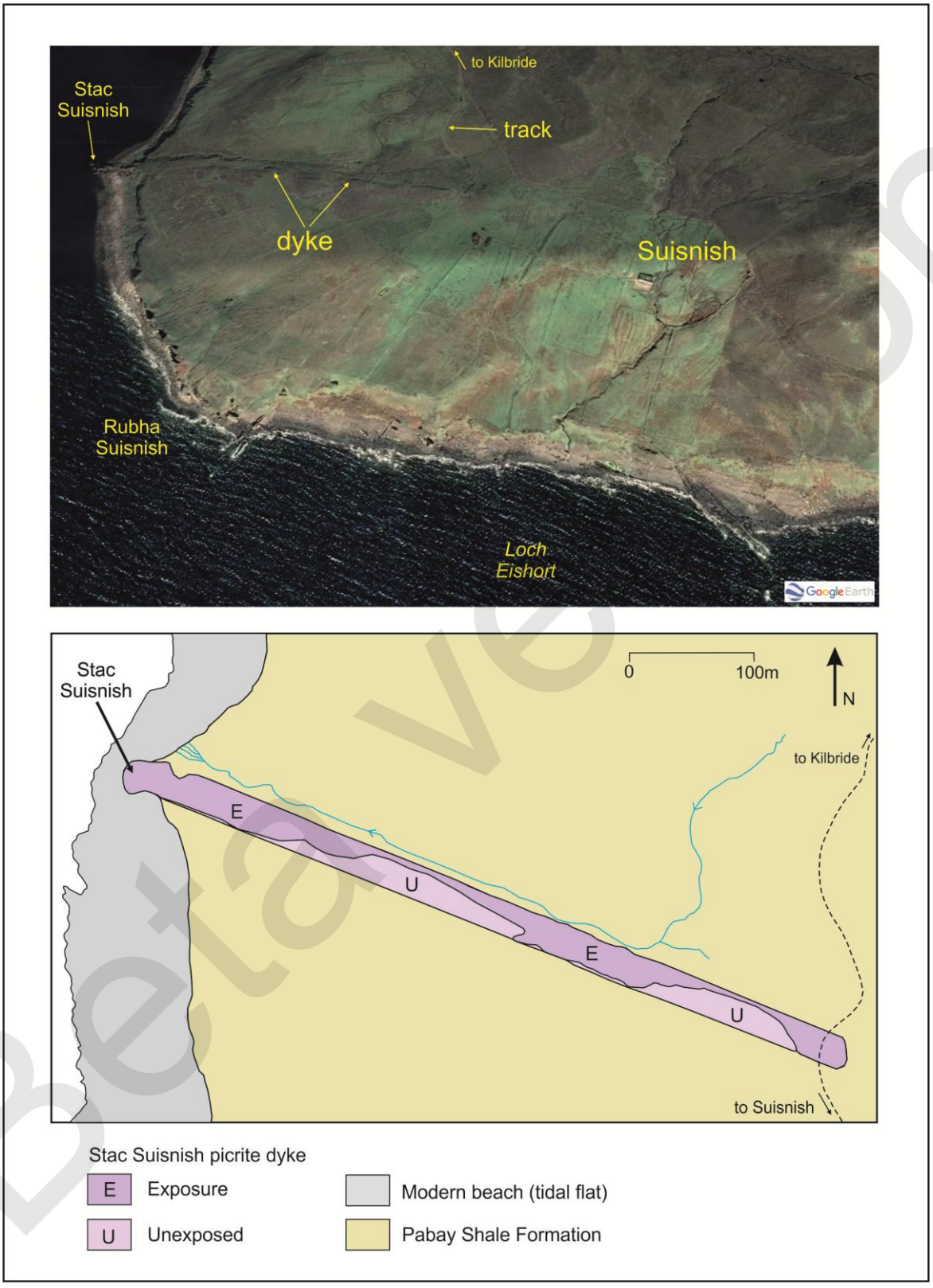


Figure 7-30: Google Earth© image and location details of the Stac Suisnish Dyke on the east side of Loch Slapin, near to the abandoned village of Suisnish, Skye.

Beta version



Figure 7-31: Inclined layers within the Stac Suisnish Dyke, on the south side of the main exposure above the High-Water Line of Loch Slapin. Layers are defined by both differing proportions of the main mafic minerals (olivine and clinopyroxene) and plagioclase, and by the presence of thin intervals with autoliths. Pole *ca.* 1 m long.



Figure 7-32: Detail illustrating the layers within the Stac Suisnish Dyke, defined by mineral proportions, crystal size and the distribution of autoliths. Length of hand lens *ca.* 50 mm.

Dyke margins are typically near planar, but where they have intruded relatively incompetent (ductile) country-rocks, the margins may be highly irregular and bounded by well-defined chilled margins. This is seen, for example, in several thin, lobate, apparently discontinuous basaltic dykes intruded into Cambro-Ordovician dolostones at Camas Malag, Skye (Figure 7-33; Figure 7-34; Figure 7-35; Figure 7-36; Figure 7-37; Figure 7-38; Figure 7-39) (Nicholson 1985).

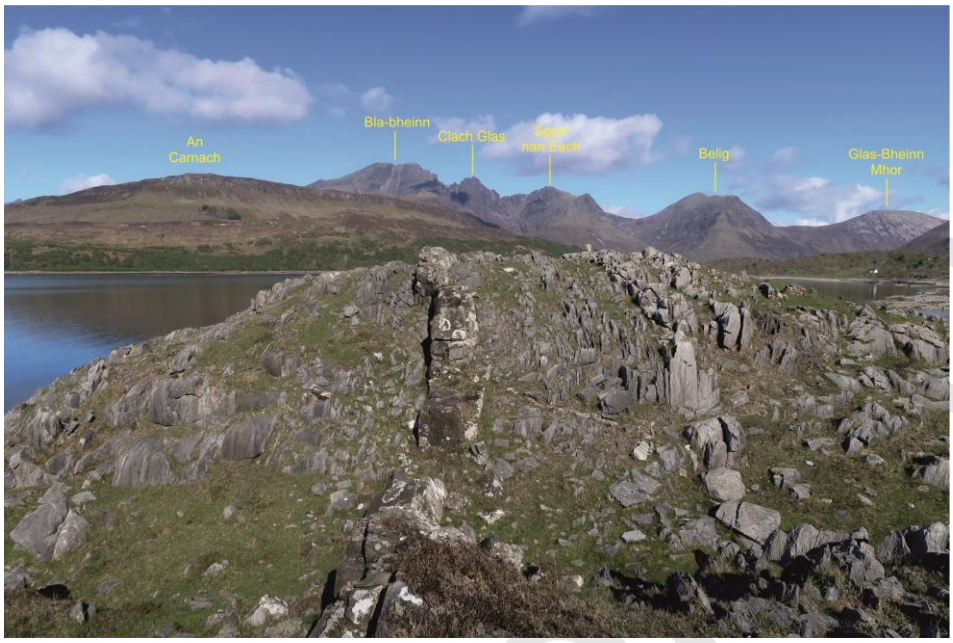


Figure 7-33: Dolerite dyke with irregular margins, intruded into Cambro-Ordovician dolostones, south of Camas Malag, Loch Slapin, Skye.



Figure 7-34: Dolerite dykes with irregular margins, intruded into Cambro-Ordovician dolostones, Torrin quarry, Torrin, Skye.



Figure 7-35: Dolerite dyke with irregular margins, intruded into Cambro-Ordovician dolostones, Torrin quarry, Torrin, Skye.



Figure 7-36: Vesicular/amygdaloidal basalt dykes, Camasunary, Skye. Pole *ca.* 1 m long.



Figure 7-37: Anastomosing basaltic dykes intruded into unstratified breccias, Runha Carach, NW Ardnamurchan.



Figure 7-38: Anastomosing basalt dyke in unstratified breccia, Rubha Carrach, NW Ardnamurchan. Pole *ca.* 1 m long.



Figure 7-39: Detail of an anastomosing basalt dyke in unstratified breccia, Rubha Carrach, NW Ardnamurchan. Pole *ca*. 1 m long.

Dykes commonly form upstanding, wall-like features, hence their name, especially where intruded into relatively easily weathered and eroded sedimentary rocks. Many examples are visible at low tide on the foreshore at Kildonnan, south Arran (Figure 7-40; Figure 7-41). Many other examples occur throughout the Hebridean Igneous Province (Figure 7-42; Figure 7-43; Figure 7-44; Figure 7-45; Figure 7-46; Figure 7-47; Figure 7-48; Figure 7-49; Figure 7-50; Figure 7-51; Figure 7-52; Figure 7-53; Figure 7-54). On the seabed between Antrim and Kintyre wall-like dykes up to 28 m in height have been identified (Fyfe *et al*. 1993).



Figure 7-40: Google Earth© image of dolerite dykes forming wall-like features ('dykes') along the foreshore at Kildonnan, south Arran.



Figure 7-41: Dolerite dyke forming a wall-like feature ('dyke') at Kildonnan, south Arran.



Figure 7-42: Basaltic dyke forming a wall-like feature ('dyke'), Gribun, west-central Mull.



Figure 7-43: Dolerite dykes intruded into more easily eroded Paleocene lavas on the east side of Ben Meabost, Strathaird, Skye, forming wall-like features ('dykes').



Figure 7-44: Dolerite dykes intruded into relatively soft Lower Jurassic Pabba Shale Formation strata on the north side of Loch Eishort, Skye, forming wall-like feature ('dykes').

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Figure 7-45: Dolerite dykes forming a wall-like features ('dykes'), Waterstein Head, Duirinish, Skye.



Figure 7-46: Dolerite dyke forming a wall-like feature ('dyke'), SW side of Beinn Iadain, Morvern.

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Figure 7-47: Cross-cutting dykes intruded into Jurassic strata, west side of Carsaig Bay, Brolass, SW Mull.



Figure 7-48: Dolerite dyke, Carsaig, SW Mull. [Photograph courtesy of James Westland]



Figure 7-49: Thick multiple dyke, Duart Point Mull. [Photograph courtesy of James Westland]



Figure 7-50: Dyke and man-made dyke 'extension', north side of Calgary Bay, NW Mull.



Figure 7-51: Inclined dyke, Port Donain coast, SE Mull. Canoe for scale.

Beta version



Figure 7-52: Prismatic-jointed dolerite dyke, Caliach Point, NW Mull.



Figure 7-53: Outweathering dolerite dyke, north Mull.



Figure 7-54: Outweathering dolerite dyke within columnar-jointed lava, Kildonan shore, SE Eigg.

In-weathered dykes are also common, for example along the east coast of Strathaird, Skye, where dolerite dykes occur within tough Middle Jurassic Bearreraig Sandstone Formation strata (Figure 7-55), and at the

Bay of Laig, Eigg, where basalt dykes occupy deep trenches between sharply defined, upstanding walls of indurated Mid Jurassic Valtos Sandstone Formation strata (Figure 7-56; Figure 7-57; Figure 7-58; Figure 7-59) (Emeleus 1997).

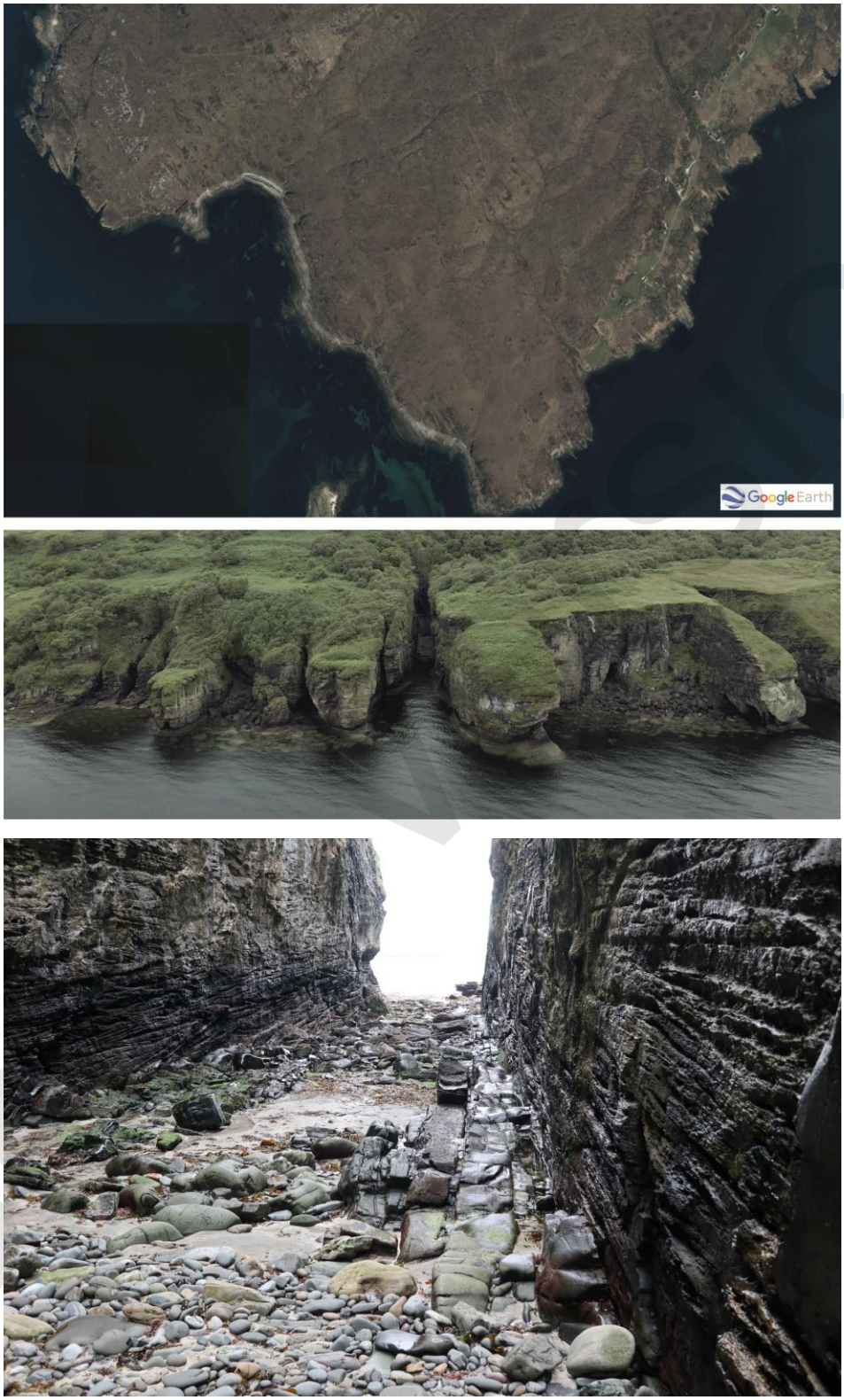


Figure 7-55: Inweathered dolerite dykes resulting in gullies along the east coast of Strathaird, Skye.



Figure 7-56: Inweathered dolerite dykes within thermally hardened country-rock Jurassic strata, Bay of Laig, west coast of Eigg.



Figure 7-57: Inweathered dolerite dykes within thermally hardened country-rock Jurassic strata, Bay of Laig, west coast of Eigg.



Figure 7-58: Detail of inweathered dolerite dyke within thermally hardened country-rock Jurassic strata, Bay of Laig, west coast of Eigg.



Figure 7-59: Detail of inweathered dolerite dyke within thermally hardened country-rock Jurassic strata, Bay of Laig, west coast of Eigg.

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Elsewhere, deep linear gullies have developed due to drainage systems utilising the differential weathering and erosion characteristics of dykes and their country-rocks, for example, Richey's Gully on the SE side of Ben Hiant, Ardnamurchan (Figure 7-60; Figure 7-61; Figure 7-62), and on the Croggan peninsula, SE Mull (Figure 7-63).



Figure 7-60: Richey's Gully, Ben Hiant, Ardnamurchan, formed by inweathered dolerite dykes.



Figure 7-61: Richey's Gully, Ben Hiant, Ardnamurchan, formed by inweathered dolerite dykes.



Figure 7-62: Base of Richey's Gully, Ben Hiant, Ardnamurchan, formed by inweathered dolerite dykes.



Figure 7-63: Inweathered dykes within basaltic lavas, SE cliffs, Croggan peninsula, SE Mull.

Columnar and prismatic joints in dykes have generally developed perpendicular to the cooling surfaces provided by the country-rocks (Figure 7-64; Figure 7-65) which helps to identify those dykes that have intruded basalt lavas or dolerite sills (with or without their own columnar joints).



Figure 7-64: Columnar jointed dolerite dyke intruded into basaltic lavas, Sròn Vourlinn, north Trotternish, Skye.



Figure 7-65: Prismatic-jointed dolerite dyke within thermally hardened country-rock Jurassic strata, Bay of Laig, west coast of Eigg.

7.2 Dyke swarms

The presence of linear dyke swarms of Paleocene age has long been recognised in NW Britain and NE Ireland. Several regional dyke swarms and localised subswarms have been identified in the HIP (Speight *et al.* 1982) of which the Skye and Mull regional dyke swarms are the most extensive. The principal features of these dyke swarms, including their dimensions (Figure 7-66), were first summarised by J E Richey and by Speight *et al.* (1982).

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Locality	Width of swarm (km)	Number of dykes per kilometre	Percentage crustal stretch due to dyke intrusion
Skye	20	299	25
Mull	20	70	10
Rum	6	40	5
Arran	23	59	12
Islay	15	23	5

Locality details: Skye, south-east of the Cuillin Centre; Mull, south-east of the Mull Central Complex; Rum, coast south-east of the Rum Central Complex; Arran, south coast; Islay Swarm crops out across Islay (Walker, 1960, fig. 1)

Figure 7-66: Dimensional data for linear dyke swarms, in the Hebridean Igneous Province.

The swarms are generally densest in the vicinity of the central complexes, where smaller subswarms of varying trends also occur, and where the dykes commonly exhibit considerable compositional diversity (Figure 7-67; Figure 7-68). Intrusion of the dyke swarms has caused pronounced local crustal dilation, the greatest amount estimated for any swarm being *ca*. 25% to the SE of the Skye Central Complex.

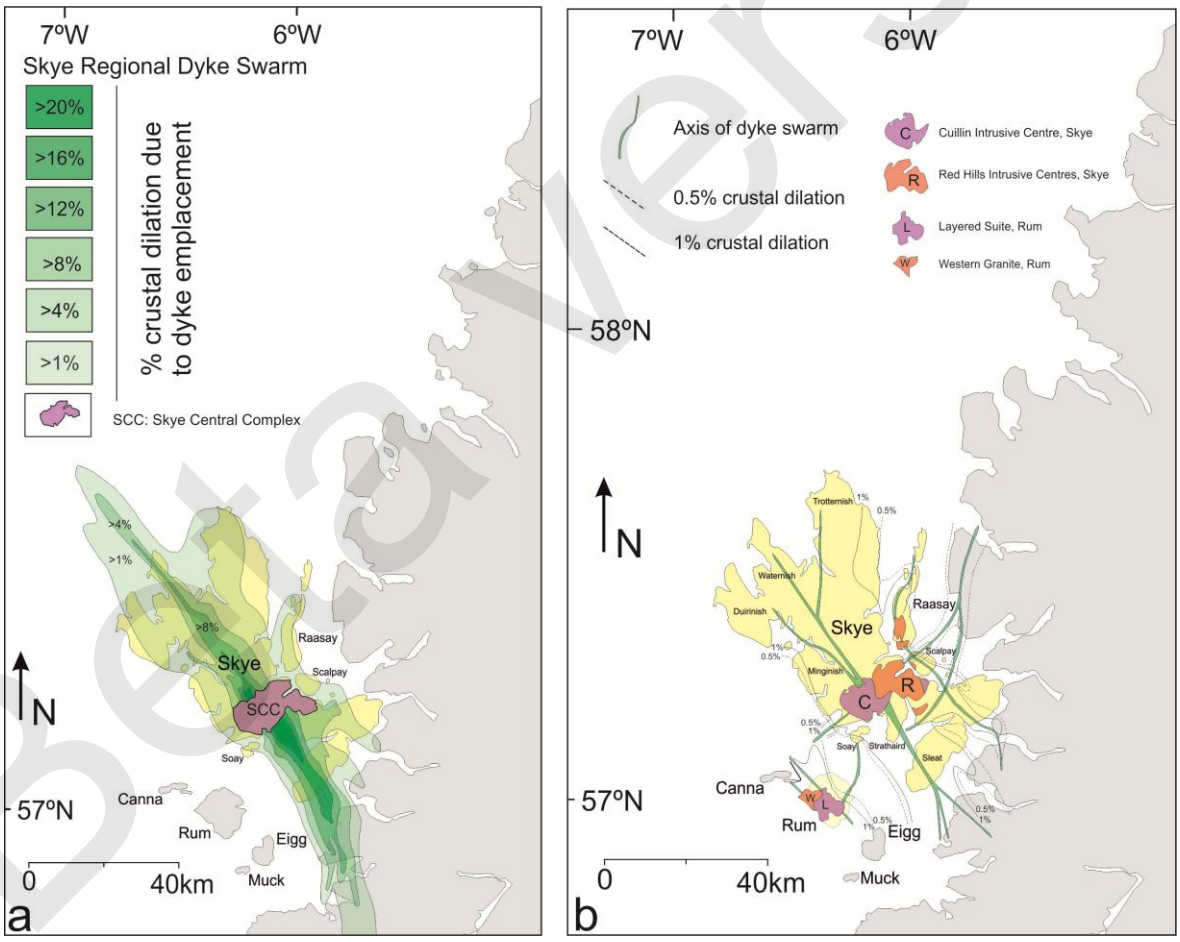


Figure 7-67: Skye linear dyke swarm, with dilation data (from Williamson & Bell 2012).

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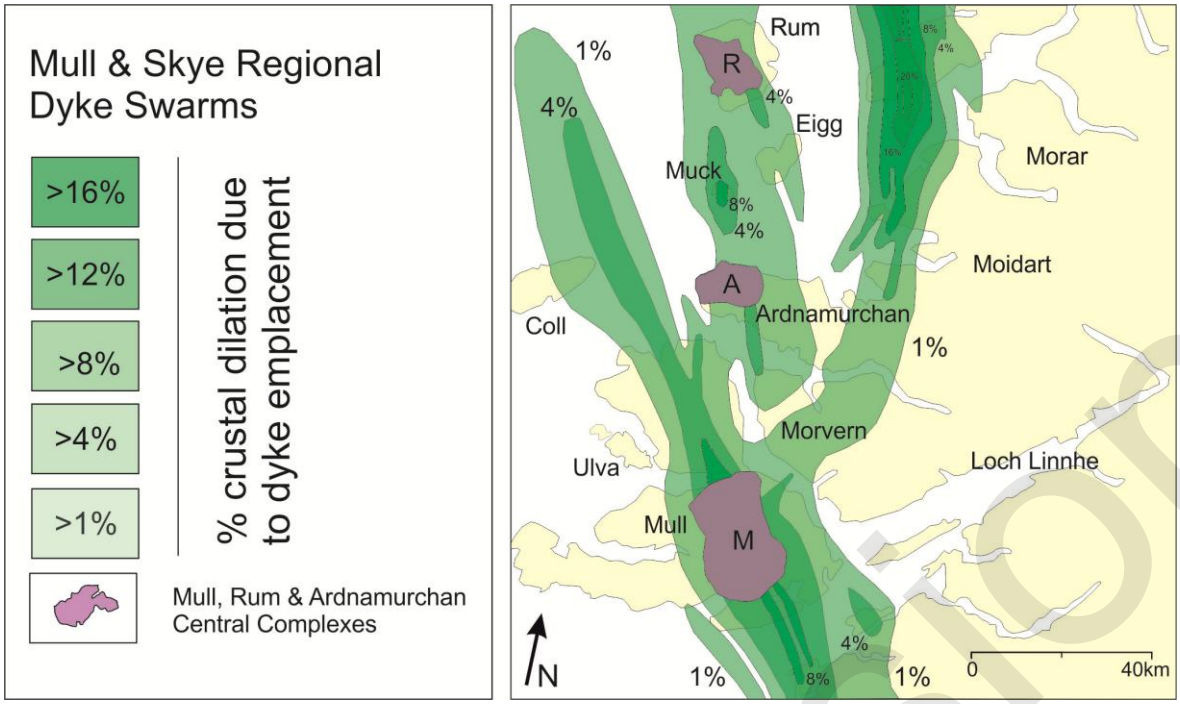


Figure 7-68: Mull linear dyke swarm, with dilation data (after Speight *et al.* 1982).

In northern Rum, the combination of dykes (and plugs) belonging to the NW-trending Muck Dyke Swarm (Figure 7-69; Figure 7-70; Figure 7-71**)** and the subsidiary N- to NE-trending Rum Subswarm simulates a radial dyke swarm focussed on the central complex (Harker 1908); it is, however, difficult to prove the presence of true radial dyke swarms in the province.



Figure 7-69: Google Earth© image illustrating the topographic 'grain' caused by the NW-SE -trending Muck Dyke Swarm.

Preliminary version



Figure 7-70: Dolerite dyke belonging to the Muck Dyke Swarm, Camas Mòr, Muck.



Figure 7-71: Dolerite dyke belonging to the Muck Dyke Swarm, west side of Port Mòr, south Muck.

The distribution of the dyke swarms was controlled by a regional NE-SW extensional stress field, and the overriding control on the orientation of the swarms is considered to have been the orientation of lower crustal intrusions that fed the dykes. Locally, subsidiary swarms are orientated approximately N-S, for

Pre-publication version

example in the Outer Hebrides, and between south Skye and Morvern, where the subsidiary swarm forms an *en échelon* link between the Skye and Mull swarms. England (1988) suggested that a minor component of dextral shear within the regional stress field controlled emplacement of the N-S dykes on Lewis, which cross-cut the pronounced regional 'grain' of the gneisses. Elsewhere, as in Morar, Moidart and Morvern, and on Arran and Ailsa Craig, upper crustal structures may have influenced the orientation of the swarms.

The structure and compositional character of the Mull Regional Dyke Swarm changes as it is traced towards the SE, away from the central complex. Jolly & Sanderson (1995) examined well-exposed shore sections between Mull and Loch Fyne and found that the multiplicity of thin dykes on and near Mull gives way south-eastwards to more widely spaced, thicker and better ordered dykes (Figure 7-72; Figure 7-73; Figure 7-74; Figure 7-75). *ca.* 500 km distant, in NE England (Figure 7-76).

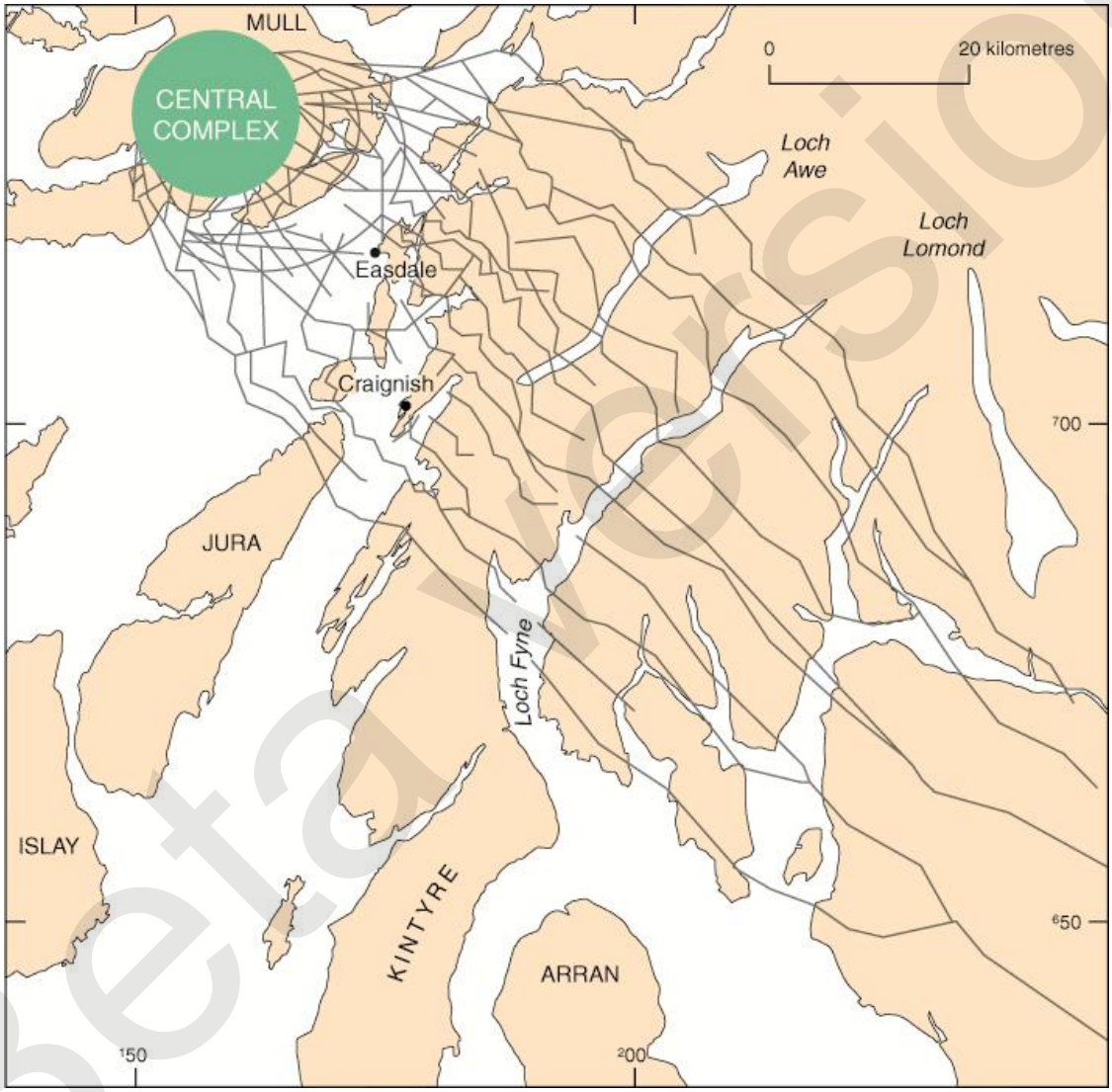


Figure 7-72: Diagrammatic representation of the Mull Dyke Swarm, SE of Mull. South-eastwards, away from the Mull Central Complex, a multiplicity of thin dykes of various orientations progressively gives way to thicker and less numerous dykes that trend predominantly NW-SE (after Jolly & Sanderson 1995).

Farther to the ESE, from Ayrshire to the extremity of the swarm in the NE of England, individual thick dykes may be traced over considerable distances. *Echelons* of the Cleveland Dyke are up to 25 m thick/wide in County Durham and north Yorkshire, some 350 to 400 km from Mull. It has been proposed that the Cleveland Dyke, which is closely similar in composition to tholeiitic basaltic rocks in Mull Central Complex, was fed laterally, in a matter of days, by a single pulse of magma that originated in the Mull

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Volcano (Macdonald *et al*. 1988). However, Speight *et al*. (1982) have contended that lateral flow of magma in dyke fissures could only have been very limited, and they postulated that the swarms were fed vertically from ridge-like basaltic magma chambers situated at depths of 20 to 50 km. They also suggested that the central complexes developed where elongate magma chambers intersected major lines of crustal weakness, such as faults. While the extent of lateral flow remains contentious, geophysical observations during active volcanism in Hawaii support the concept (e.g. Walker 1993).



Figure 7-73: Dolerite dyke, Kerrera, SE of Mull, part of the Mull Main Dyke Swarm.



Figure 7-74: Dolerite dyke, Kerrera, SE of Mull, part of the Mull Main Dyke Swarm.

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Figure 7-75: Dolerite dyke, Kerrera, SE of Mull, part of the Mull Main Dyke Swarm.



Figure 7-76: The Cleveland, Dyke, a distal intrusion of the Mull Main Dyke Swarm in NE England.

The close relationships between the dyke swarms and the central complexes (see above) are evident. The abundance of dykes in the country-rocks, including the lava fields, contrasts with their scarcity within many members of the central complexes, although there is much detailed evidence of substantial overlap in time between emplacement of dyke swarms and the intrusion of successive members of the central complexes. In Skye, many NW-SE -trending basic dykes intrude both the lavas and the gabbros of the Cuillin Intrusive Centre, from Blà-bheinn and Sgùrr na Stri in the SE (Figure 7-77; Figure 7-78; Figure 7-79), to the NW part of the Cuillin at Sgùrr an Fheadain; the dykes both cut and are cut by cone-sheets (Chapter 9). On Rum, thin basaltic dykes occur within the Western Granite.



Figure 7-77: Thick dolerite dyke intruded into gabbro, east side of Blà-bheinn, Skye.

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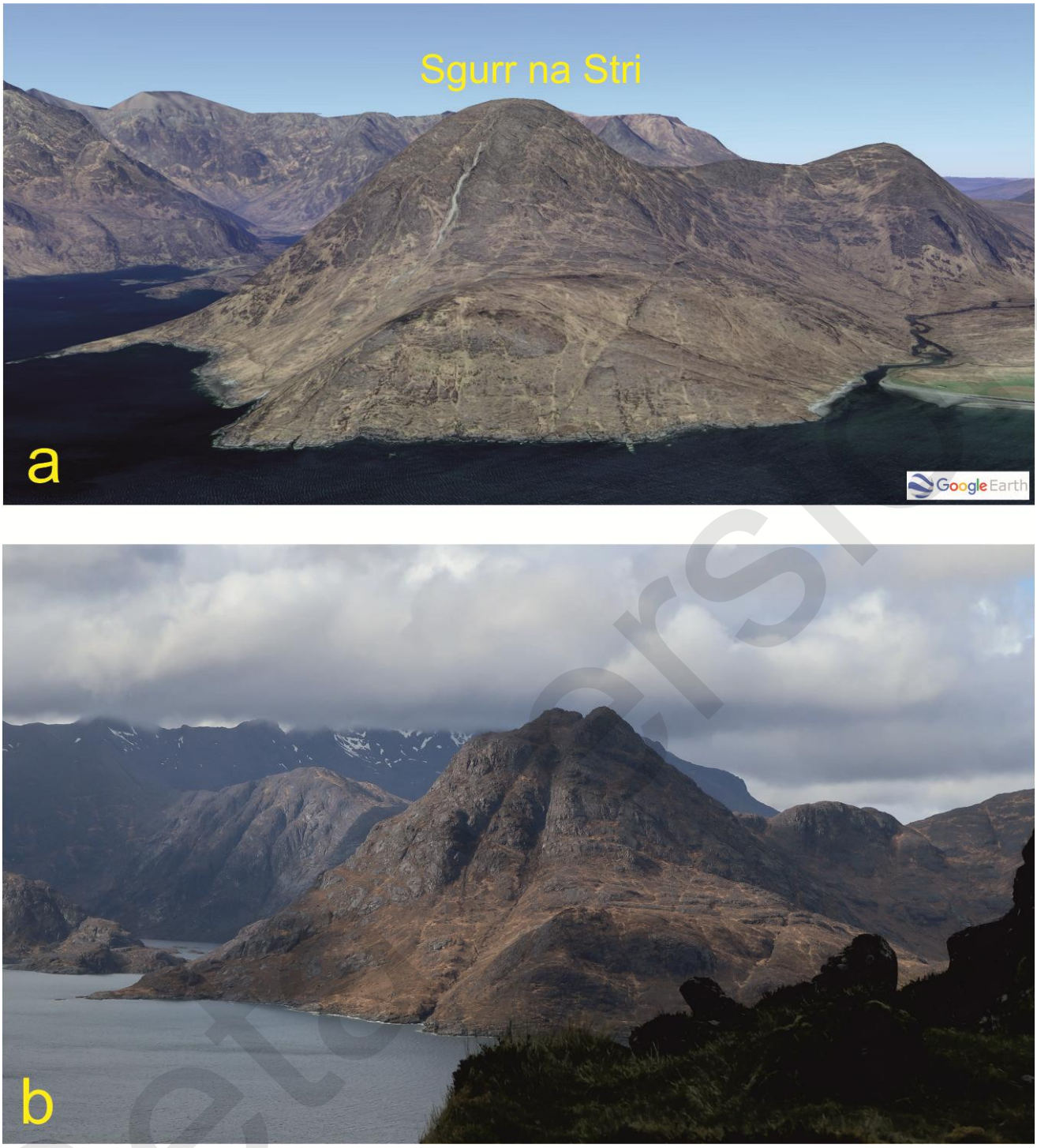


Figure 7-78: (a) Inclined Google Earth© image of Sgùrr na Stri in the SE sector of the Cuillin, a focus of dyke emplacement, and a field view of Sgùrr na Stri from Carn Mòr, Strathard.

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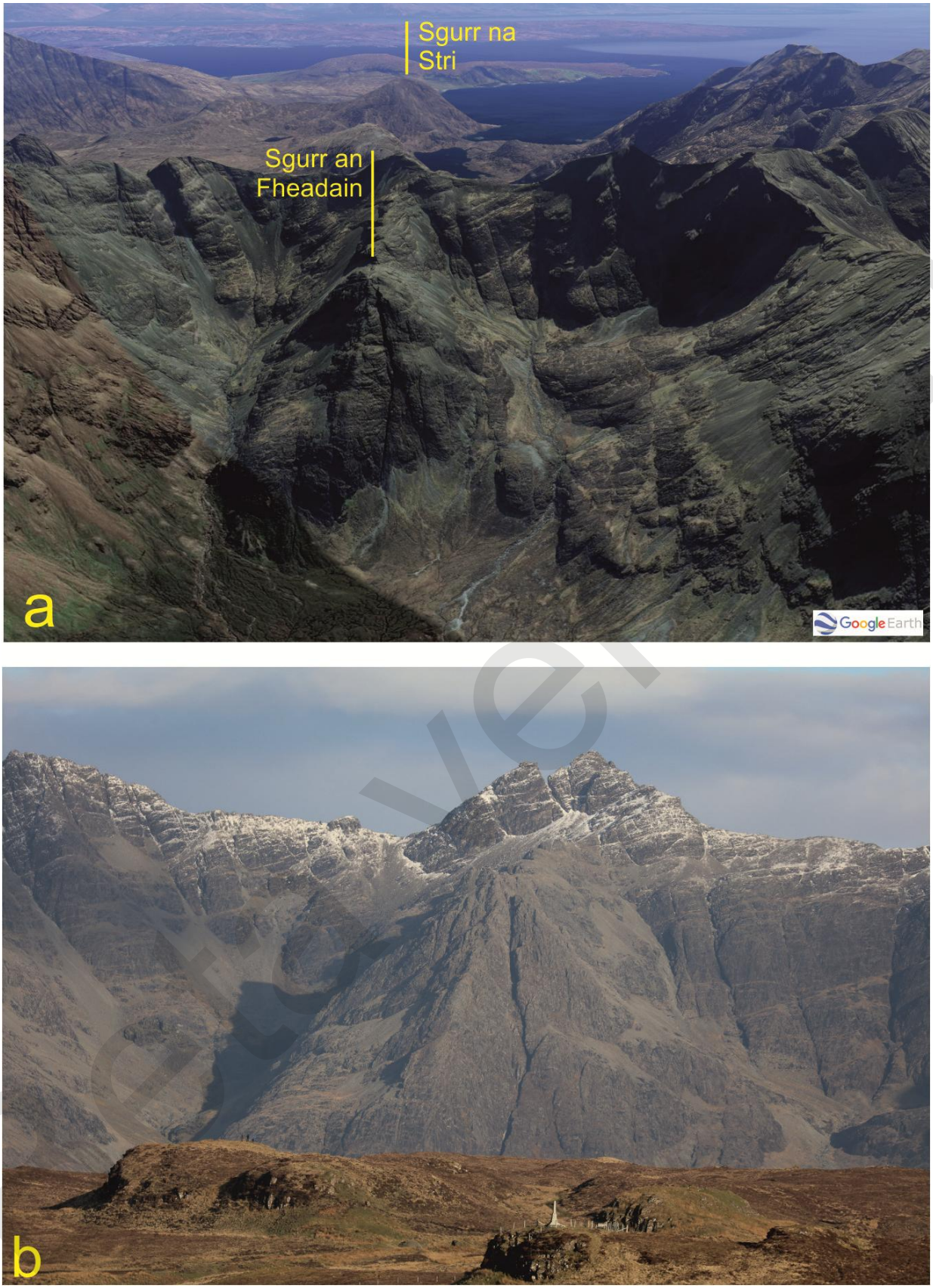


Figure 7-79: (a) Inclined Google Earth© image of Sgùrr an Fheadain in the NW sector of the Cuillin, a focus of dyke emplacement, and a field view of Sgùrr an Fheadain from Carbost.

By comparison, far fewer NW-SE-trending dykes intrude the younger Red Hills granites on Skye (Figure 7-80; Figure 7-81; Figure 7-82) and the Western Granite on Rum (Figure 7-83).



Figure 7-80: Dark, steeply inclined dolerite dykes within the Ruadh Stac Granite (on Ruadh Stac), Red Hills, Skye. View towards the SE from Marsco, Skye.



Figure 7-81: Dark basaltic dykes within orange-weathered granite, Beinn Dearg Mhòr - Beinn Dearg Mheadhonach, Western Red Hills, Skye.

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Figure 7-82: Dark dolerite dyke within orange-weathered granite, Beinn na Caillich, Skye.

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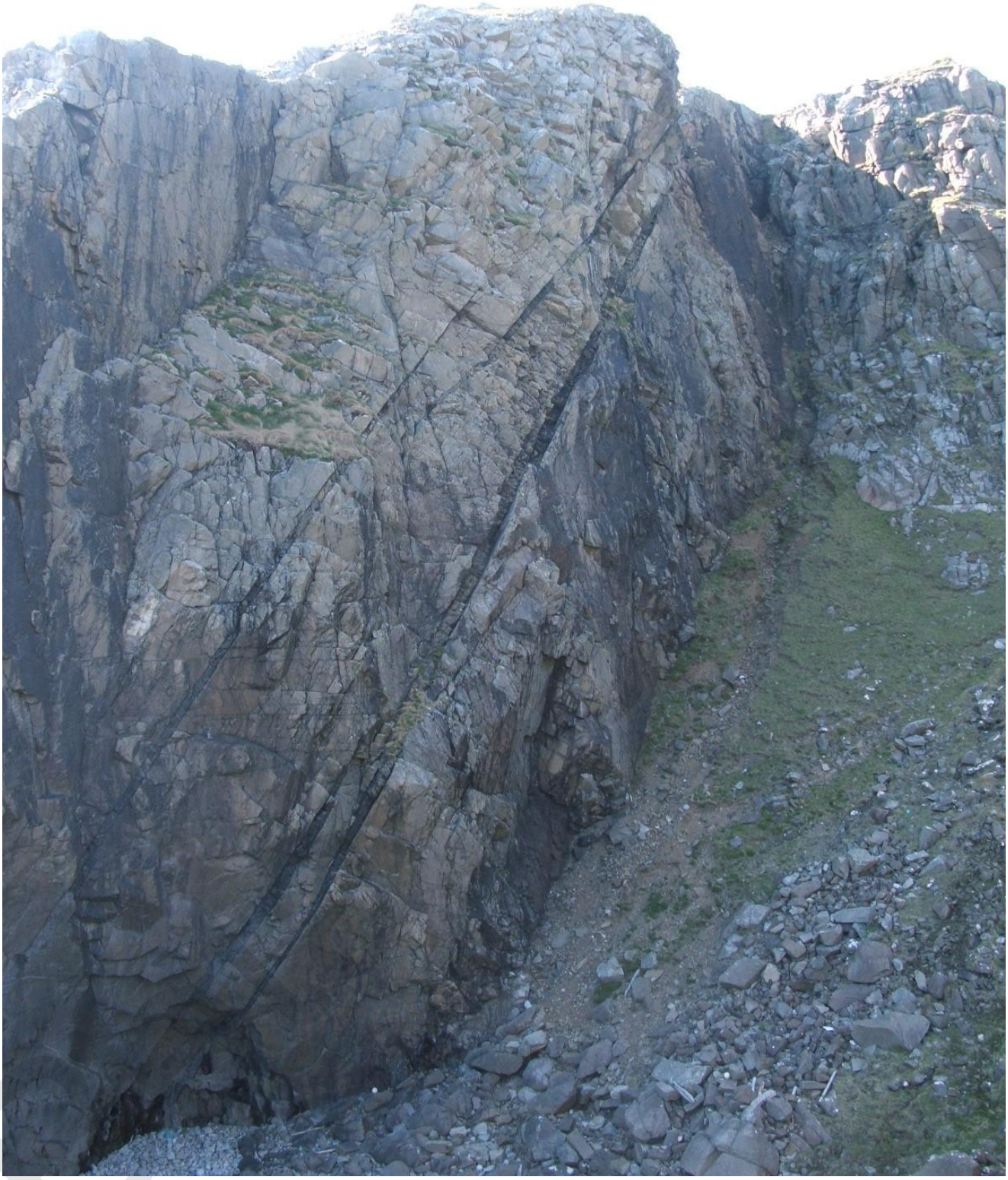


Figure 7-83: Thin basaltic dykes within the Western Granite, SW Rum.

On Rum, Eigg and Muck, many dykes belonging to both the regional Muck Swarm and the Rum Subswarm intrude earlier members of the Rum Central Complex (Chapter 9), but the later layered intrusions postdate most of the dykes.

On Mull, NW-SE -trending basic dykes intrude most members of the Mull Central Complex but appear to be less numerous than in the surrounding lavas. This view is supported by evidence from the shores of Loch na Keal, where up to one-third of the dykes are free from the pervasive pneumatolytic alteration that affects their host lavas around the Mull Central Complex. On Ardnamurchan, only a few dykes cut the intrusions of Centres 2 and 3, although they are common in the country-rocks, and a number cut pre-Centre 2 cone-sheets. Members of the NNW-trending Arran Dyke Swarm intrude the North Arran Granite Pluton, but in fewer numbers than are seen in the country-rocks. Few dykes are found in the Central Arran Ring-complex.

With few exceptions (e.g. the Canna Lava Formation in NW Rum and on Canna and Sanday), the majority of the dykes in the regional swarms and subswarms appear to postdate the Paleocene lava fields surrounding the central complexes. While it is generally assumed that many of the lavas were fed from the dykes, or from plugs that developed on dykes (see below), it is extremely rare to find an example of a dyke feeding a lava. It must be concluded that dyke intrusion was continuous, albeit with diminishing intensity, throughout the growth of the lava fields and the central complexes. In general, the dyke swarms appear to be intimately linked to specific central complexes, although the association of the Islay and Kintyre-Jura dyke swarms with the submarine Blackstones Bank Central Complex (Chapter 9) cannot be proved (Walker 1960). Emplacement of a dyke swarm may, therefore, have taken place over a million years or more (Chapter 5) and the individual swarms may have been separated by even more substantial periods of time. As with the lavas, there was no single period of dyke emplacement in the Hebridean Igneous Province during the Paleocene.

7.3 Dyke composition

Most of the dykes of the regional swarms are of basaltic or slightly more evolved composition. In and around the central complexes there are, additionally, dykes of silicic, intermediate and, less commonly, ultrabasic composition (Gibb 1968, 1969). Two types of ultrabasic dykes are recognised: xenolithic peridotites, with randomly oriented cognate xenoliths; and, non-xenolithic types, commonly referred to as picrites (Figure 7-84; Figure 7-85; Figure 7-86). On Skye, they are informally referred to as the Ben Cleat and Coire Lagan types, respectively.

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Figure 7-84: Xenolithic ultrabasic dyke, An Leac, north side of Soay Sound, Skye. Pole *ca.* 1 m long.



Figure 7-85: Detail of xenolithic ultrabasic dyke, An Leac, north side of Soay Sound, Skye, with sub-angular fragments of banded troctolite in a picrite matrix. Coin *ca.* 24 mm across.



Figure 7-86: Coire Làgan Type ultrabasic dyke, intruded into Outer Bytownite Troctolites, SW of the unnamed lochan in Coire Làgan, Cuillin, Skye. Pole *ca*. 1 m long.

The basaltic dykes of the regional swarms are predominantly of tholeiitic basalt or tholeiitic olivine basalt (the so-called Preshal More (PM) Magma-type), or of mildly alkaline olivine basalt (the so-called Skye Main Lava Series (SMLS) Magma-type), or the uncommon Fairy Bridge (FB) Magma-type (Chapter 10) (Figure 7-87) (Mattey *et al*. 1977). Dyke compositions may remain uniform over considerable distances, as is well demonstrated in regional dykes that extend across the Southern Uplands and into north Yorkshire (Macdonald *et al*. 1988).

Tholeiitic basalts and related, more evolved, lithologies predominate in the Mull Regional Dyke Swarm. However, alkali olivine-dolerites, locally termed 'crinanites', are common as far SE as Loch Fyne, and the swarm contains silicic and intermediate dykes in the vicinity of Oban and on Mull.

The dykes intruding the Skye Central Complex and its immediate surroundings have a wide compositional range (Chapter 10). Sporadic NW-SE -trending dykes of vitrophyre ('silicic pitchstone') (Figure 7-88) and alkali olivine-dolerite intrude the granites of the Red Hills intrusive centres, and abundant earlier dykes of tholeiitic basalt and alkali olivine basalt overlap emplacement of the gabbros and the Coire Uaigneich Granite of the Cuillin Intrusive Centre (Chapter 9). Ultrabasic dykes are principally found close to the central complex, although a few ultrabasic dykes, rich in calcic plagioclase, intrude the Paleocene lavas near Bracadale, NW of the Cuillin Intrusive Centre (Figure 7-89) (Donaldson 1977).

Dyke orientation (NW-SE) of the Skye swarm is maintained where the (Lewisian) gneisses are intruded in south Sleat (Figure 7-90).

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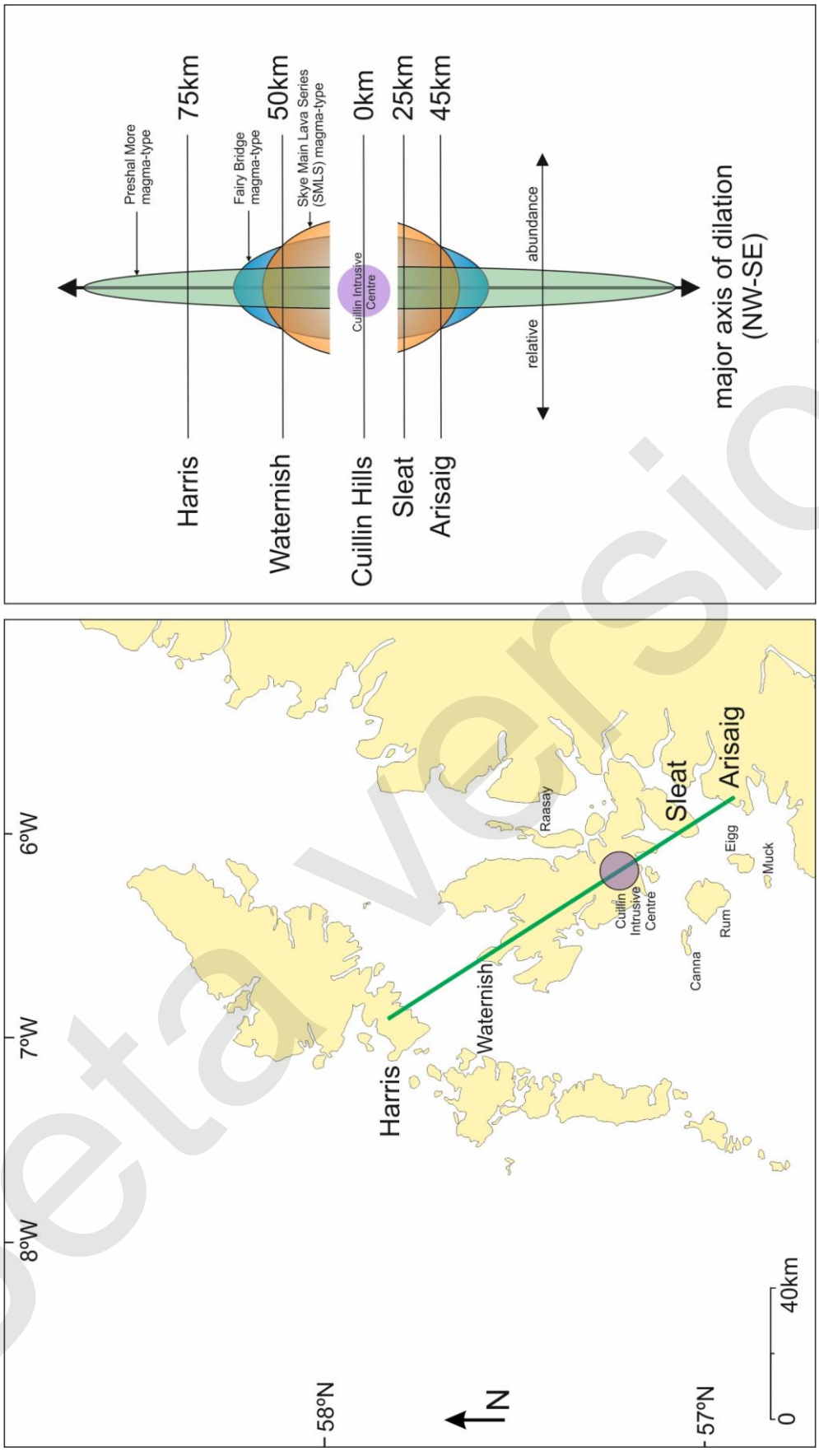


Figure 7-87: Map and schematic diagram showing locations of dyke traverses and relative abundance data of the three magma types (after Mattey *et al*. 1977).

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Figure 7-88: (a) Vitrophyre dyke, SE of Coire-chat-achan, Strath, view towards the SE, pole *ca*. 1 m long; and, (b) detail of inclined 'rodded structure' on margin of dyke, coin *ca*. 24 mm across

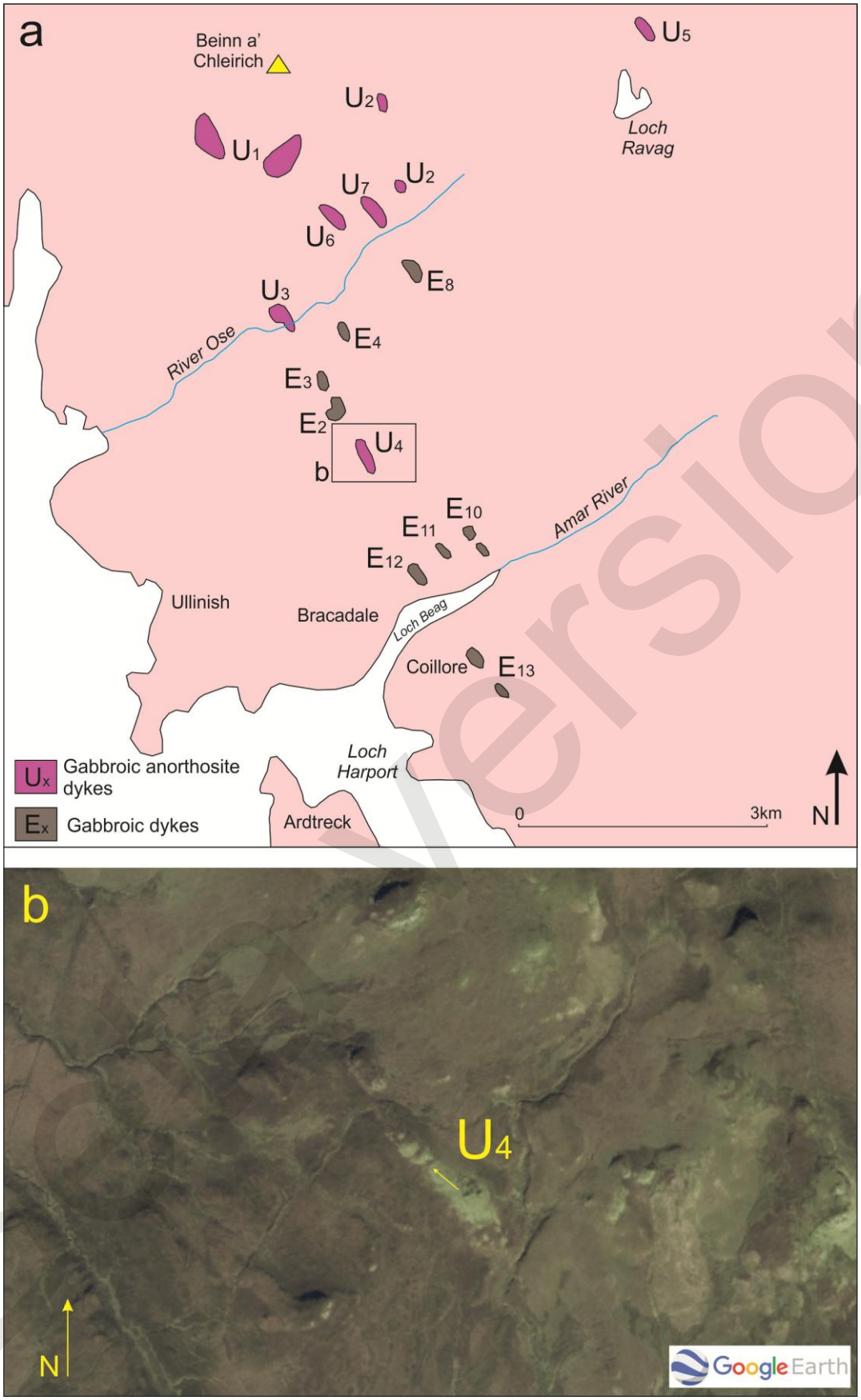


Figure 7-89: (a) Simplified location map for the ultrabasic (troctolitic) dykes of Bracadale (after Donaldson 1977); and, (b) Google Earth© image of outcrop area of dyke U_4.

Review version



Figure 7-90 : Prismatic-jointed dolerite dyke intruded into gneiss of the Moine Thrust Sheet, south Sleat, Skye.

NW-SE -trending trachyte dykes occur along the axis of the Skye Regional Dyke Swarm, for example in the vicinity of Drynoch, on Loch Harport and at Coire-chat-achan, Strath. (Figure 7-91; Figure 7-92).



Figure 7-91: Trachyte dyke of the Skye Regional Dyke Swarm, roadcut north of Loch Bracadale, Minginish, Skye. Pole, on margin of dyke, *ca*. 1 m long.



Figure 7-92: Trachyte dyke, SW of Coire-chat-achan, Strath, Skye.

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The dykes on Rum are generally composed of transitional olivine basalt, less commonly of tholeiitic basalt and basaltic andesite, and very rarely of vitrophyre (Forster 1980). Additionally, the Rum layered intrusions are cut by rare picritic basalt dykes, which most likely represent quenched ultrabasic liquids (Upton *et al.* 2002). The dykes of Eigg, which belong to the Rum Subswarm, are principally transitional to mildly alkaline olivine basalts with a few more evolved hawaiites and mugearites, and rare feldspar-phyric dolerites. The dykes of the Muck Dyke Swarm on Muck are generally less evolved than those on Eigg and Rum and include a high proportion of mildly alkaline olivine-dolerites.

On Rum, Canna and Sanday, a few NW- to NE-trending dykes of olivine basalt and dolerite intrude the Canna Lava Formation. They are either late members of the Rum Subswarm or, more likely, related to younger activity on Skye. No trachytic dykes are known from the Small Isles.

The Islay and Jura–Kintyre dyke swarms consist of mildly alkaline olivine-dolerites and evolved variants, including hawaiite; on Jura, a small subswarm is of a primitive picrobasalt composition.

Along the south coast of Arran, members of the Arran Dyke Swarm exposed in the classic Kildonnan shore section range in composition from alkali olivine-dolerite ('crinanite') to tholeiitic olivine basalt, tholeiitic basalt and quartz-dolerite. The alkali olivine-dolerite dykes of Arran may be earlier than the tholeiitic basalt dykes, since the latter intrude the Central Arran Ring-complex and the North Arran Granite Pluton, whereas the former do not. Vitrophyres (silicic pitchstones) occur in some abundance on Arran where they intrude the North Arran Granite Pluton. There is also a number of composite dykes with quartz-dolerite or tholeiitic basalt margins (commonly containing xenocrysts of quartz and rare alkali feldspar) and quartz-feldspar porphyry or contaminated porphyritic central parts. They are of similar composition to the composite sills on Arran (Chapters 8 and 10).

A *ca.* 70 cm thick monchiquite dyke containing xenoliths of mantle and deep-crustal origin, and a variety of megacrysts, crops out at Loch Roag on the Isle of Lewis (Figure 7-93; Figure 7-94) (Menzies *et al.* 1987; Faithfull *et al.* 2012). It has an anomalously young isotopic age of 45.2 ± 0.2 Ma (Faithfull *et al.* 2012) and trends ENE-WSW, at variance with the majority of the Paleocene dykes on Lewis. This dyke, an alkaline lamprophyre containing olivine, titanaugite, biotite-phlogopite, oxides and turbid analcime, is quite unlike any other dyke recorded from the Hebridean Igneous Province but can be tolerably matched with Eocene and Oligocene intrusions in West and East Greenland.

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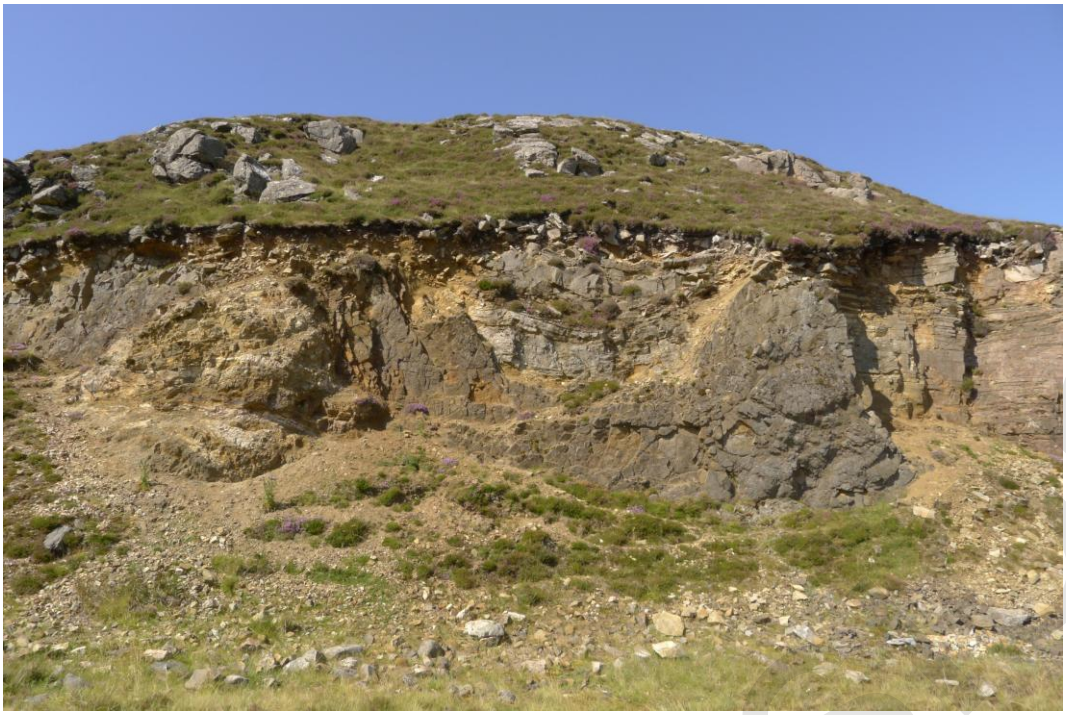


Figure 7-93: Loch Roag xenolithic monchiquite dyke, Abhainn Uasaig, near Carishader, Lewis, Outer Hebrides, intruded into granitic gneiss of the Lewisian Gneiss Complex (parallel to the face of the rock face). [Photograph courtesy of John Faithfull]



Figure 7-94: Peridotite xenolith of Mantle derivation within the Loch Roag Dyke, Lewis, Outer Hebrides. [Photograph courtesy of John Faithfull]

7.4 Volcanic plugs

Volcanic plugs are of widespread occurrence in the HIP but are most common in and around the central complexes and in the lava fields. There is a very large concentration on Rum, where more than forty plugs of gabbro, dolerite and peridotite intrude the Torridonian and Triassic sedimentary rocks and most members of the central complex (Figure 7-95). The gabbro plugs may have fed surface flows, but no compositional match can be made with any of the lavas preserved on Rum. The ultrabasic plugs of Rum contain magnesium-rich olivine and calcic plagioclase, compositionally akin to the minerals in the Rum layered intrusions (Wadsworth 1994).

The plugs range from a few tens of metres to over one kilometre in diameter. Their plan view may be nearly circular but is more commonly oval or elongate. Where elongate, the long axes of the plugs are generally aligned in the direction of the regional dyke swarms, NW-SE, as, for example, at 'S Airde Beínn and other localities in northern Mull (Figure 7-96). However, on Rum, elongate plugs appear to radiate from the central complex.

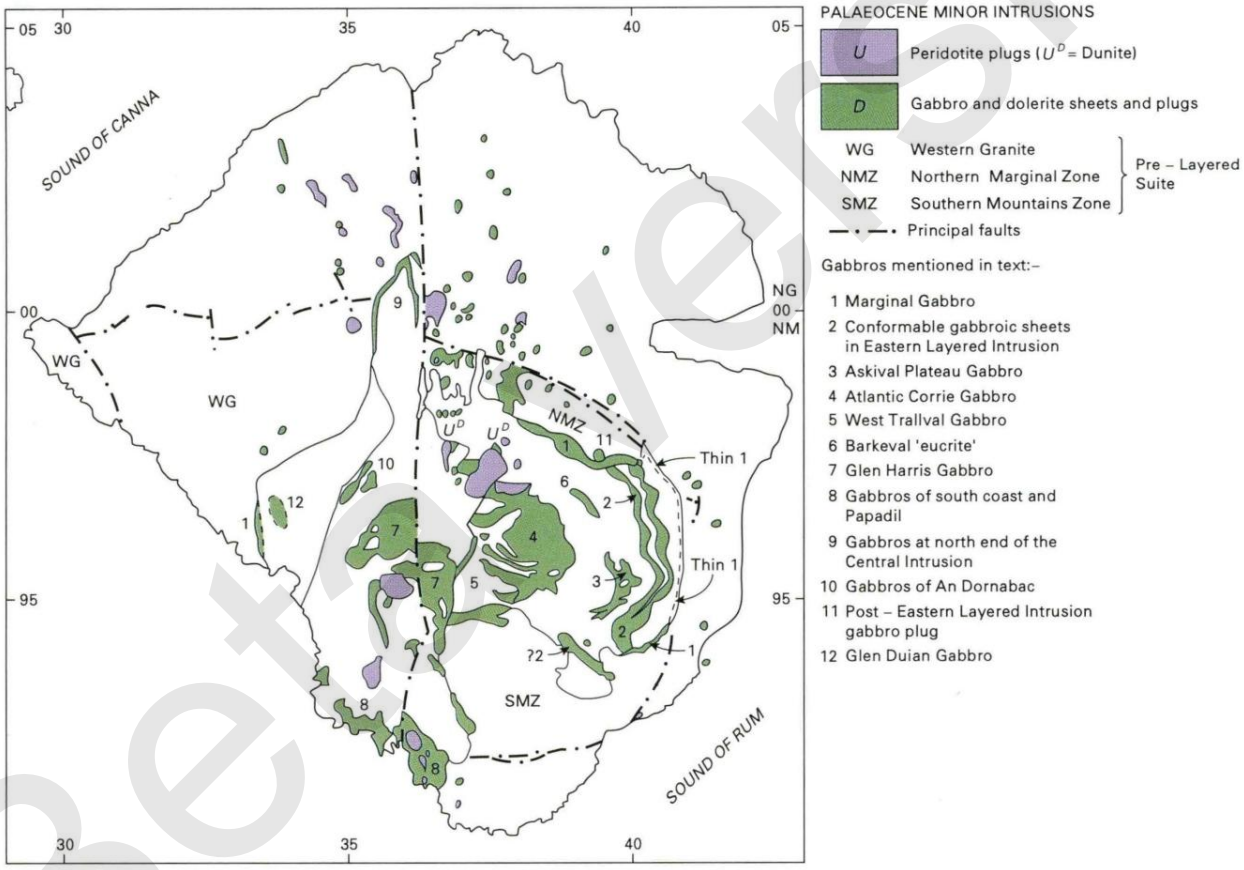


Figure 7-95: Distribution of gabbro sheets and plugs, and peridotite plugs in the Rum Central Complex and surrounding rocks (after Emeleus 1997).

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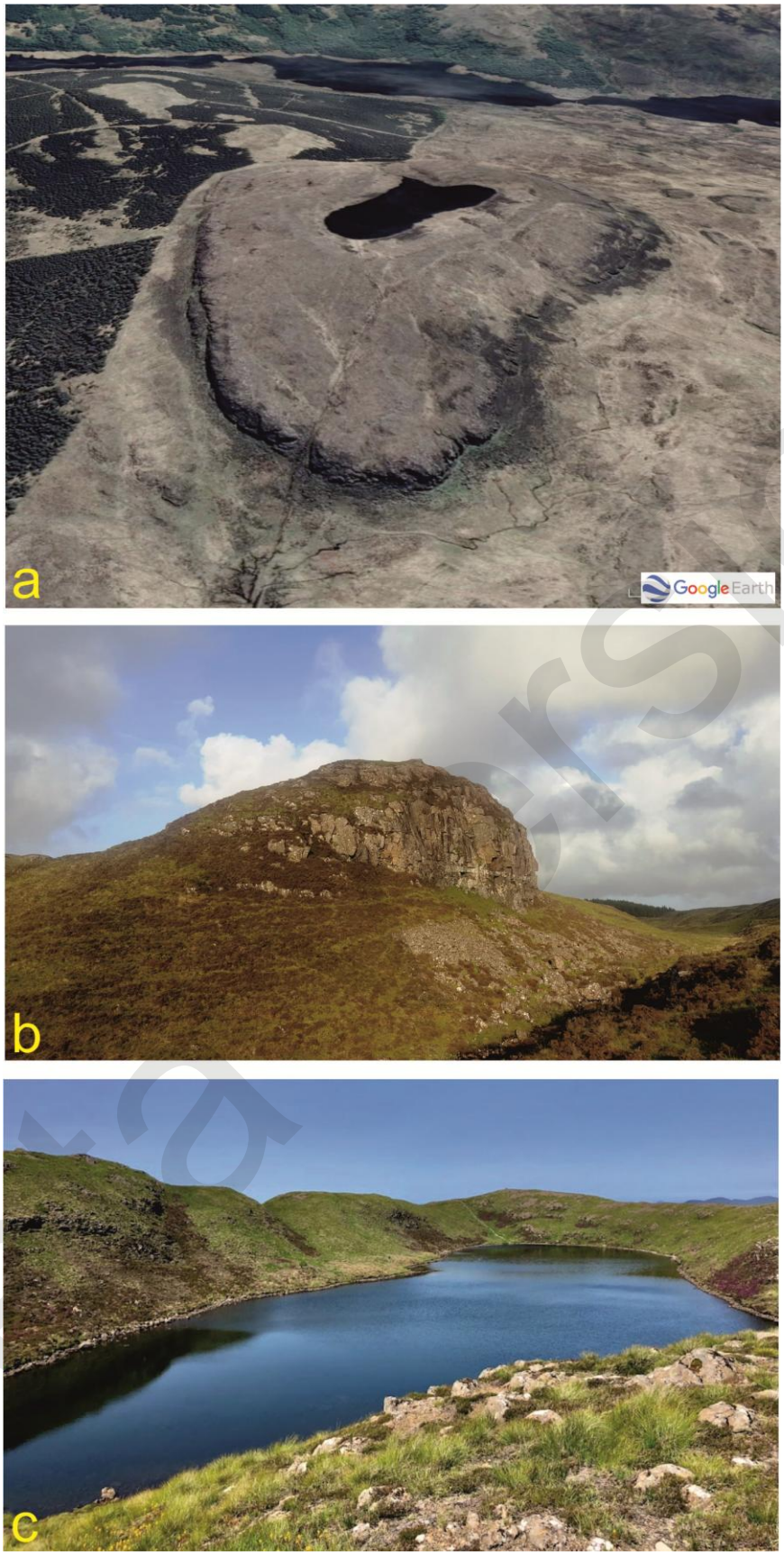


Figure 7-96: (a) Oblique Google Earth© image, and (b) & (c) field views of the 'S Airde Beinn plug, west of Tobermory, NE Mull. [Photographs courtesy of James Westland]

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On Islay, a NNW-elongated olivine-dolerite plug, or boss, at Cnoc Rhaonstil is considered to be the distended head of a dyke in the Islay Dyke Swarm (Hole & Morrison 1992). Several of the thicker dykes in the HIP are of limited lateral extent and may be elongate plugs, possibly related to volcanic necks, as in Antrim. Examples include the dolerite mass that intrudes granite on the NE shoulder of Beinn na Caillich, Skye (Figure 7-82), and the olivine-dolerite of Gualainn na Sgùrra that is intruded into lavas near the east end of the Sgùrr of Eigg.

The majority of the plugs are basaltic in composition, but a few of trachyte composition have been recorded. On Mull, a large trachyte plug intrudes lavas and is, itself, intruded by NW-SE -trending dykes at Druim Buidhe, SE of Tobermory. On Ardnamurchan, a plug of biotite trachyte intrudes psammites of the Moine Supergroup east of Ben Hiant. The dolerite plug at Cnoc Rhaonstil, Islay, is unusual in exhibiting considerable internal variation in composition and texture, with marked alkali enrichment (Hole & Morrison 1992; Preston *et al.* 1998b; Chapter 10).

Basalt or dolerite plugs intruded into the lava fields may easily escape detection unless they form distinct topographical features. This may account for their apparent absence from the Skye Lava Field. However, they may not occur there as they have not been identified among the adjacent and relatively well exposed Mesozoic sedimentary rocks. Several plugs intrude the lavas of northern Mull (e.g. Kerr 1997) and include the olivine-dolerite at 'S Airde Beínn (Figure 7-96**)** which has produced a pronounced thermal aureole in the surrounding lavas and was almost certainly a feeder for lava flows (Cann 1965), as were a number of the other plugs on Mull. Several plugs of Mg-rich tholeiitic dolerite have, however, no compositional equivalents among the lavas and most likely acted as feeders for flows subsequently removed by erosion. The lavas of Eigg and Muck are cut by rare dolerite plugs; on Muck the only plug is an alkali olivine-dolerite.

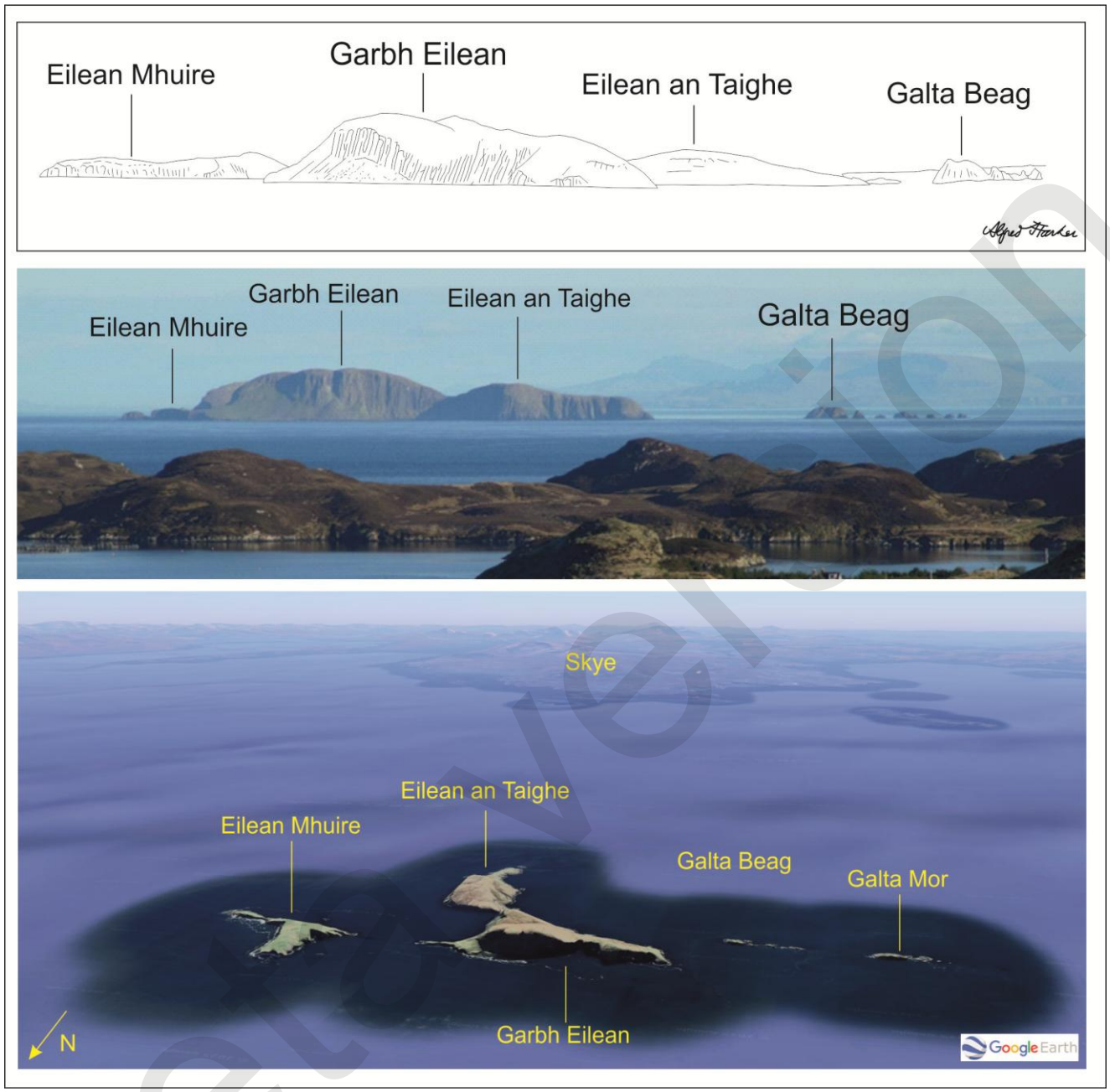
Sedimentary and metasedimentary rocks intruded by plugs are commonly thermally metamorphosed. On Rum, high-grade thermal alteration of the Torridonian feldspathic sandstones surrounding the gabbroic plugs involved partial melting and the formation of tridymite around larger quartz grains; limited fusion of sandstone, to form buchite, is also present. The mineralogy of the altered sandstone adjoining a gabbroic plug in Kinloch Glen indicates that the thermal alteration occurred when the sedimentary rocks were buried under as little as 500 m cover of strata (Holness 1999). By contrast, alteration of sandstone around the peridotite plugs of Rum is generally restricted to induration and discoloration of the sedimentary rocks, with evidence of only limited melting; since the peridotites were emplaced carrying large amounts of suspended olivine crystals, their heat capacity and ability to affect their surroundings was apparently much reduced.

Several olivine-dolerite plugs intrude Moine metasedimentary rocks east of the Ardnamurchan Central Complex where, in Glenmore, a plug has caused a limited amount of fusion of the feldspathic country-rocks to form buchite.

Alteration of the Dalradian meta-mudstone around the Cnoc Rhaonstil plug on Islay is slight; however, the Dalradian meta-siltstone surrounding a plug of coarse olivine-dolerite at Sithean Sluaigh, south of Strachur on Loch Fyne (Scottish Mainland), is intensely altered and its foliation has been deformed to parallel the margins of the plug. Here, partial melting has resulted in granophyric veins and refractory residual material containing mullite, magnetite, corundum and spinel (Smith 1969).

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8 Sills and sill-complexes



The Shiant Isles, dominated by a thick Paleocene picrite sill

8.1 Introduction

Sills and sill-complexes are intimately associated with the Paleocene lava fields and central complexes of the Hebridean Igneous Province (HIP). In general, the sills occur within the Mesozoic sedimentary sequences below the lavas, although on Mull the Loch Scridain Sill-complex also intrudes the overlying Paleocene lava field. Thus, the depth of emplacement of the upper parts of the sill-complexes is relatively shallow, most likely less than 1 km. Individual sills can vary from less than 1 m thick, up to several tens of metres, and exceptionally over 100 m. Bifurcations, transgressions and terminations are common. Locally, the country-rocks may be disturbed and chilled margins are generally well developed, although thermal alteration of country-rocks is typically localised. It is difficult to estimate the total (preserved)

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thickness of each of the sill-complexes due to a lack of continuous vertical sections and the fact that many of them continue below sea level. However, it is likely that they are at least a few hundreds of metres thick.

Each sill-complex has its own distinctive compositional signature, unrelated to the typically older lava sequences. Alkali olivine basalt and tholeiitic basalt magmas are represented, together with their fractionation products (trachyte and rhyolite, respectively). Magma mixing between basaltic and silicic magmas is recognised in some sills and may be a significant process in the evolution of some sill-complexes. Intra-sill variation in mineral proportions may be due to a variety of processes, including crystal settling or flotation and flow differentiation. Crustal contamination of the sill magmas may be deduced from whole-rock isotopic characteristics (Chapter 10). Xenoliths are rare, except within the Loch Scridain Sill-complex.

The two main sill-complexes are: (a) the Little Minch Sill-complex, of alkali olivine basalt affinity in north Skye, Raasay and the Shiant Isles; and, (b) the Loch Scridain Sill-complex, of tholeiitic basalt affinity in SW Mull.

In south Arran there are several unrelated groups of sills of very different compositions, including: the Holy Island and Dippin sills of alkaline affinity; and various microgranite/porphyritic rhyolite sills.

Certain groups of sills show clear spatial and temporal relationships with the central complexes. These include composite sills (basaltic andesite-rhyolite) associated with the Mull Central Complex and the Eastern Red Hills Intrusive Centre of Skye. Other groups of composite sills show no obvious link to central complexes, for example those in south Arran and south Bute. The thick microgranite sill in south Raasay is most likely related to the nearby granitic intrusions of the Western Red Hills Intrusive Centre on Skye.

Ultrabasic sills are much less common and are generally associated with the central complexes. Typically, they are modally layered, with alternating olivine- and plagioclase-rich layers, as exemplified by the Gars-bheinn Sill on the southern margin of the Cuillin Intrusive Centre of Skye.

8.2 Little Minch Sill-complex

8.2.1 General characteristics

The Little Minch Sill-complex crops out on Trotternish, north Skye, and forms almost all the Shiant Isles, with more restricted outcrops on Waternish and Duirinish (north Skye) and the west coast of Raasay. The extent of the complex, as much as 4,000 km^2, is illustrated in Figure 8-1, which is based on offshore geophysical data (Chesher *et al.* 1983). Significant submarine outcrops occur within the Little Minch, between Skye and Harris.

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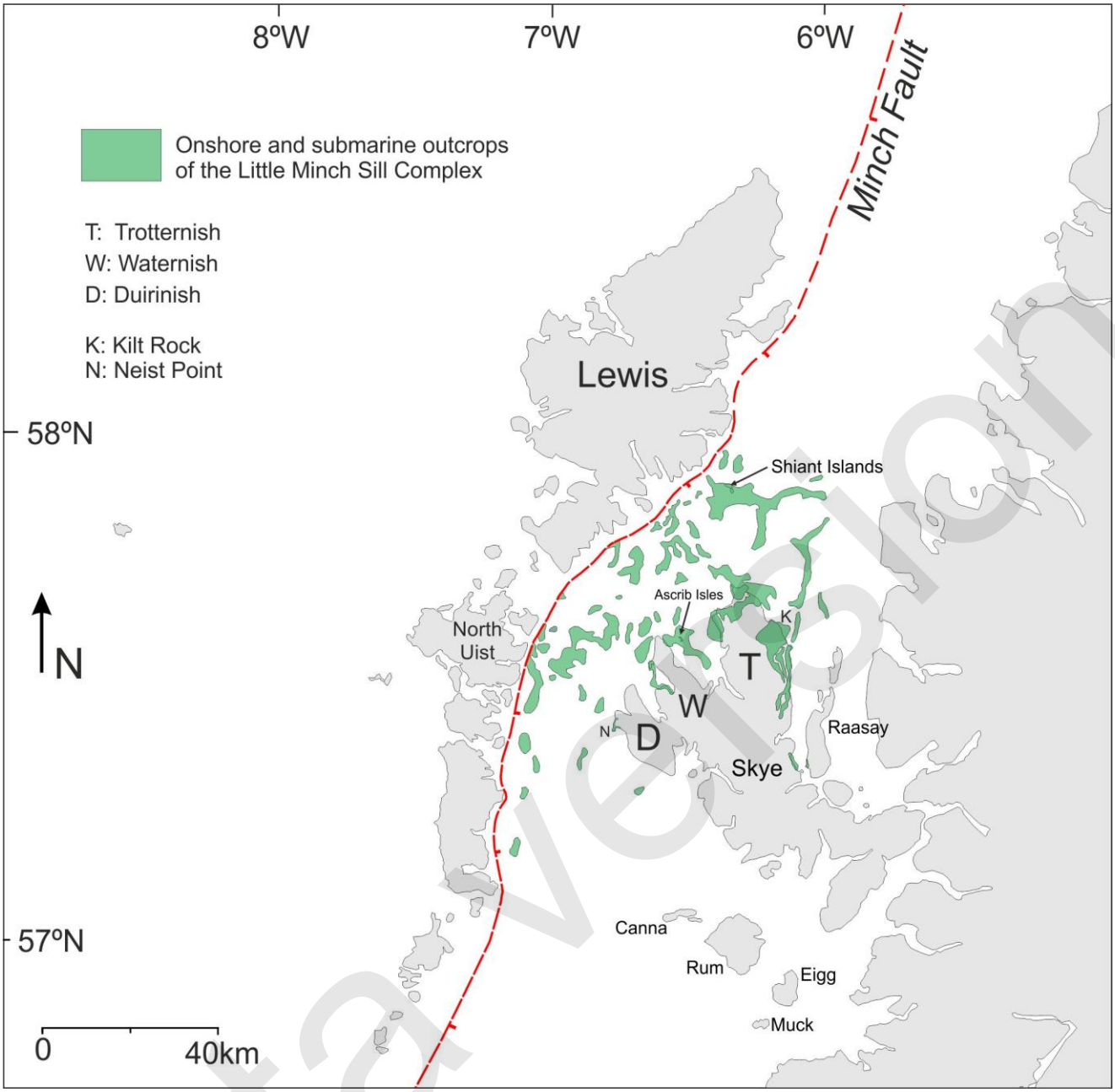


Figure 8-1: The onshore and submarine outcrops of the Little Minch Sill Complex (after Gibb & Gibson 1989).

At different localities (Figure 8-2), total sill thicknesses are relatively constant at *ca*. 250 m, with individual sills typically in the range 10-130 m, commonly achieving thicknesses in excess of 90 m, for example, at Meall Tuath and Meall Deas, NW Trotternish, Skye (Figure 8-3; Figure 8-4; Figure 8-5; Figure 8-6). On a gross scale, the sills are tabular, concordant with the host Jurassic strata, but with local transgressions.

Due to the present-day level of erosion, upper contacts of the sills are rare. Access to some of the best sections through the sills on Trotternish is, at best, difficult, and in places not possible, restricting observations to be from adjacent cliff tops or from a boat (Figure 8-7; Figure 8-8; Figure 8-9; Figure 8-10; Figure 8-11) (Schofield *et al*. 2016).

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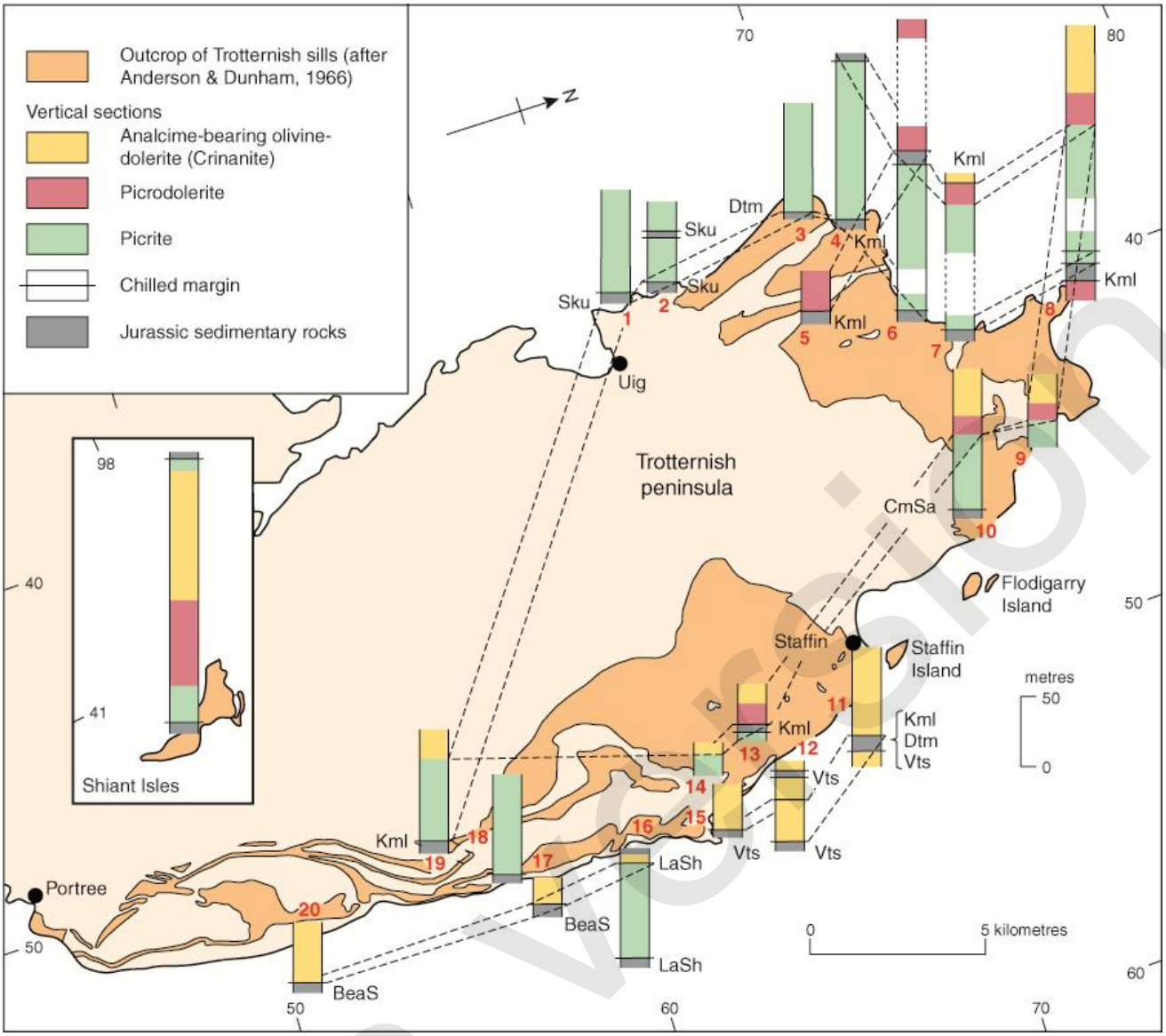


Figure 8-2: Igneous stratigraphy of the Little Minch Sill Complex at selected localities on Trotternish and the Shiant Isles. Country-rock Jurassic strata (undifferentiated) are also indicated. Based on Gibson & Jones (1991) and Emeleus & Bell (2005). Key to localities: 1: Skudiburgh; 2: Kilbride Point; 3: Sgeir Lang; 4: Bornesketaig; 5: Heribusta; 6: Osmigarry; 7: Creagan Iar; 8: Meall Tuath; 9: Balmaqueen; 10: Flodigarry; 11: Staffin; 12: Loch Mealt; 13: Dùn Raisaburgh; 14: Culnaknock; 15: Dùn Connavern; 16: Inver Tote; 17: Leac Tressirnish; 18: Rigg; 19: Tottrome; 20: Bearreraig Bay. Jurassic sedimentary rocks: BeaS: Bearreraig Sandstone Formation; LaSh: Lealt Shale Formation; Vts: Valtos Sandstone Formation; Dtm: Duntulm Formation; Kml: Kilmaluag Formation; Sku: Skudiburgh Formation; CmSa: Carn Mor Sandstone Formation.

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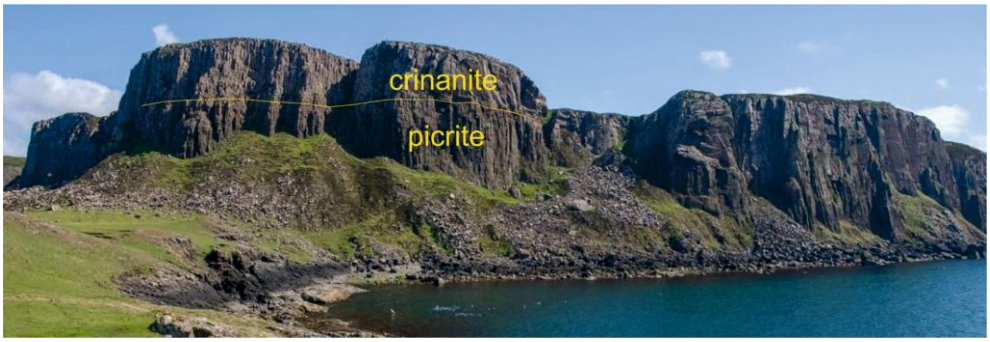


Figure 8-3: View south to the cliffs below Meall Tuath (middle) and Meall Deas (right), north Trotternish, Skye, comprising a lower (younger) picrite unit and an upper crinanite (alkali olivine dolerite) unit.



Figure 8-4: View SE to the cliffs below Meall Tuath, north Trotternish, Skye, comprising a lower (younger) picrite unit and an upper crinanite (alkali olivine dolerite) unit.



Figure 8-5: The cliffs at Meall Deas, NW Trotternish, Skye, composed (predominantly) of prismatic-jointed picrite, Person for scale.

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Figure 8-6: The cliffs at Lùb a' Sgiathain, north Trotternish, Skye, composed of a columnar-jointed, multiple/composite sill, with (lower) picrite, (middle) picrodolerite and (upper) crinanite (alkali olivine dolerite) units.



Figure 8-7: The cliffs at Balmaqueen, north Trotternish, Skye, composed of a columnar-jointed, multiple/composite sill, with (lower) picrite, (middle) picrodolerite and (upper) crinanite (alkali olivine dolerite) units.



Figure 8-8: Prismatic-jointed picrite sill forming the coastline north of Bornesketaig on the NW coast of Trotternish, Skye. View is east towards Gairbh-sgeir at the southern end of Lùb an Sgòir. Cliff is *ca*. 40 m high.

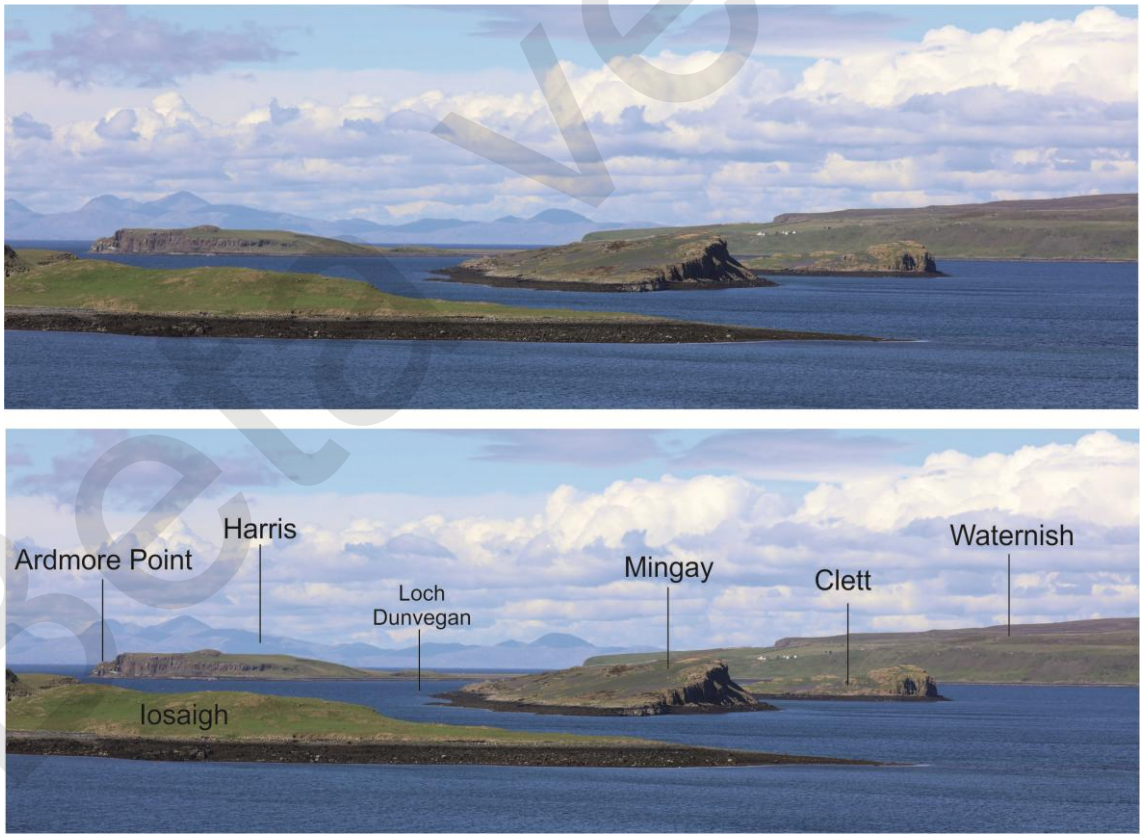


Figure 8-9: Inclined olivine dolerite sill(s) forming the islands of Mingay and Clett, Loch Dunvegan. Waternish, the island of Ìosaigh and the headland at Ardmore Point are composed of Palaeocene lavas.

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Figure 8-10: Eilean Garve, Ascrib Islands, Loch Snizort, composed of an inclined olivine dolerite sill. [Photograph courtesy of The Jack Russells, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=153821899]



Figure 8-11: Layered olivine dolerite sill, Eilean Creagach, Ascrib Islands, Loch Snizort [Photograph courtesy of John Allan, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=133474213]

The Little Minch Sill-complex postdates the emplacement of the Skye Lava Group (Chapter 6) and has a shallow dip towards the west (Figure 8-12; Figure 8-13).



Figure 8-12: A transgressive multiple olivine dolerite sill (right-hand side) of the Little Minch Sill-complex intruded into Paleocene basaltic lavas forming the cliff of Biod Bàn at the southern end of Oisgill Bay on the west coast of Duirinish. View towards the north.



Figure 8-13: Detail of a transgressive multiple olivine dolerite sill of the Little Minch Sill-complex intruded into Paleocene basaltic compound lavas forming the cliff of Biod Bàn at the southern end of Oisgill Bay on the west coast of Duirinish. View towards the north.

Preview version

Studies by Drever & Johnston (1965) and Anderson & Dunham (1966) are concerned predominantly with the field relationships and petrography of the sills. These investigations identified their alkaline nature, ranging in composition from olivine-rich picrite and picrodolerite, through to more evolved analcime-bearing olivine-dolerite ('crinanite').

Stratification ('layering') is common in some of the least evolved sills; good examples occur at Duntulm Castle (Figure 8-14; Figure 8-15; Figure 8-16), Rubha Hunish (Figure 8-17; Figure 8-18) Eilean Flodigarry (Figure 8-19), Meall Tuath and the Ascrib Islands, all on or just offshore north Trotternish. The Duntulm Castle and Rubha Hunish outcrops are most likely of the same sill. Simkin (1967) developed a model involving flow differentiation and gravity settling or flotation processes to explain the mineralogical variation and layering within certain of the sills. Stratification tends to occur mostly within picritic units and is commonly found adjacent to contacts with the country-rocks. It is typically on a centimetre to decimetre scale, involving variations in texture and in the proportions of olivine, clinopyroxene and plagioclase. However, such layering can also occur within a sill adjacent to rafts of sedimentary rock, implying that heat loss from the magma may have been important in the development of layering. Furthermore, there is little field or petrographical evidence to suggest that crystal settling has taken place to any significant extent. Thus, an *in situ* crystallisation model is preferred to account for the stratification/layering (Gibson & Jones 1991).



Figure 8-14: The layered picrite sill below the ruins of Duntulm Castle on the coast of NW Trotternish, Skye. Height of cliff is *ca*. 20 m. The layered character of the sill is due to the relative proportions of the main minerals, with dark layers dominated by olivine and pyroxene, grading into paler layers with a higher percentage of plagioclase.

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Figure 8-15: Detail of the layered character of the picrite sill below the ruins of Duntulm Castle.



Figure 8-16: Detail of the layered character of the picrite sill below the ruins of Duntulm Castle, with a lower (relatively plagioclase-rich) layer 'overlain' (with a sharp boundary/interface) by the base of a darker more olivine- and pyroxene-rich layer. Note insipient (hydrothermal) alteration along steeply inclined cooling joints. Hammer *ca.* 30 cm long.



Figure 8-17: Layered picrite sill forming the headland of Rubha Hunish, NW Trotternish, Skye.



Figure 8-18: Detail of layered picrite sill forming the headland of Rubha Hunish, NW Trotternish, Skye.



Figure 8-19: Layered, columnar-jointed picrite sill, NE face of Eilean Flodigarry, off Flodigarry, Trotternish.

On Trotternish, where the columnar- and prismatic-jointed sills are responsible for much of the impressive coastal scenery (Figure 8-20; Figure 8-21; Figure 8-22; Figure 8-23; Figure 8-24; Figure 8-25; Figure 8-26; Figure 8-27**),** the sill-complex can be seen to be transgressive, invading progressively younger Jurassic strata towards the north.

Be



Figure 8-20: The Kilt Rock on the east coast of Trotternish, Skye, at Ealaiseadar, composed of an upper columnar-jointed crinanite sill, a horizontally bedded sequence of Valtos Sandstone Formation strata, and a lower columnar-jointed crinanite sill. Cliff is *ca.* 90 m high. Compare sections to the left and to the right of the waterfall. View towards the north from Rubha nam Brathairean.



Figure 8-21: The Kilt Rock on the east coast of Trotternish at Ealaiseadar, composed of an upper columnar-jointed crinanite sill, a horizontally bedded sequence of Valtos Sandstone Formation strata, and a lower (at sea level) columnar-jointed crinanite sill. Cliff is *ca.* 90 m high. View towards the north from the Kilt Rock Viewpoint (Aite-faire Creag an Fhèilidh).

Preview version



Figure 8-22 : Columnar-jointed crinanite sills with intervening Valtos Sandstone Formation strata, Kilt Rock viewpoint (for scale), Trotternish.

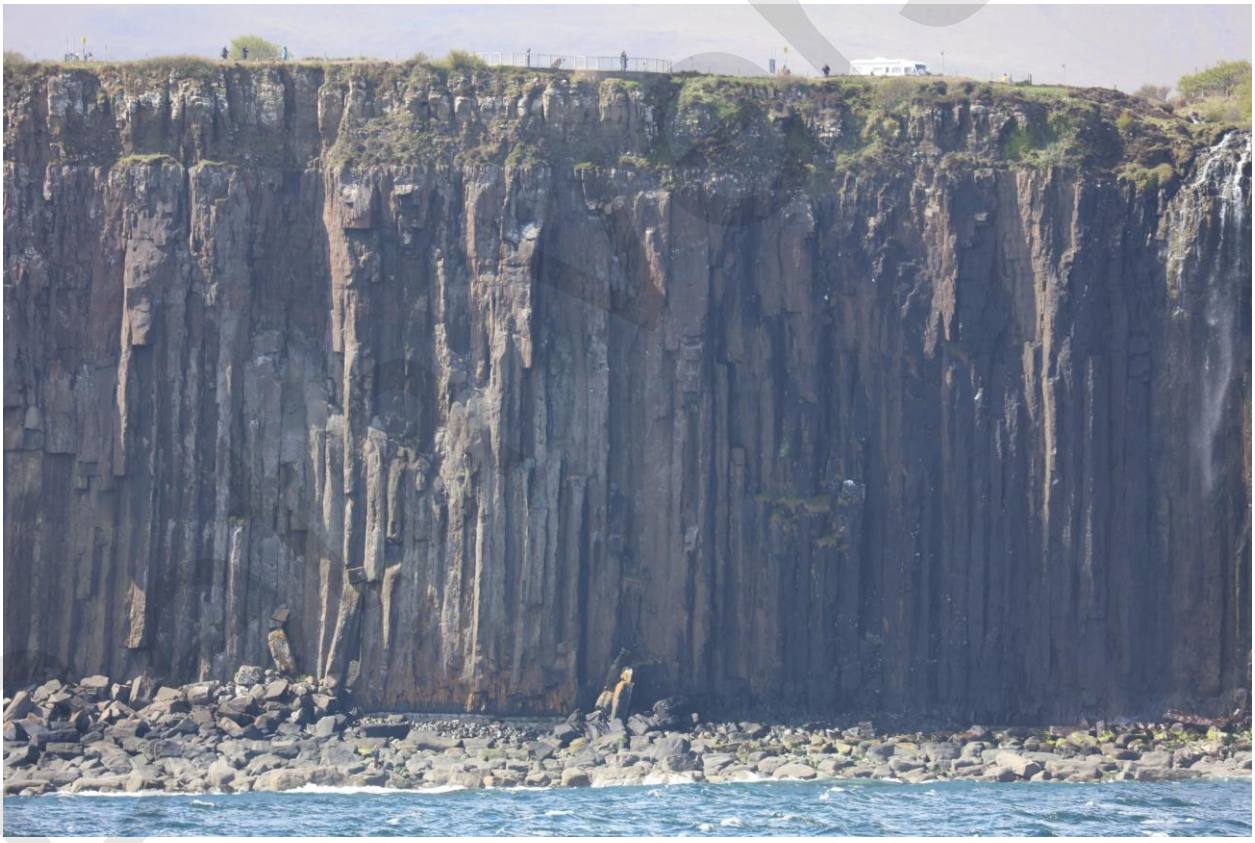


Figure 8-23: Columnar-jointed crinanite sill at the Kilt Rock viewpoint,Trotternish, with people for scale.

Draft version



Figure 8-24: Columnar-jointed dolerite sill forming the upper part of the sea cliff south of Rigg, west coast of Trotternish. The lower part of the cliff comprises host Middle Jurassic Bearreraig Sandstone Formation sandstones. In the distance, forming the inland escarpment, are Paleocene basaltic lavas of the Beinn Edra Formation, in part landslipped with detached blocks forming The old Man of Storr and Needle Rock. View towards the SW.



Figure 8-25: Columnar-jointed sills within host Middle Jurassic Lealt Shale Formation strata south of Rubh nam Brathairean, Trotternish.



Figure 8-26: Columnar-jointed sills within host Middle Jurassic Lealt Shale Formation strata south of Rubh nam Brathairean, Trotternish.



Figure 8-27: Columnar-jointed dolerite sills within host Middle Jurassic Valtos Sandstone Formation strata south of the Kilt Rock viewpoint, Trotternish.

The sills can either be simple (one lithology), multiple, or composite involving some combination of picrite, picrodolerite and alkali olivine-dolerite. Where sills are composite, the lower unit tends to be the least evolved. The internal contacts between different units can provide evidence of their relative age, with many based on the development of chilled margins and joint patterns.

Thermal metamorphism of country-rocks is typically localised, within a few metres, exceptionally +10 m, of the margin of the sill. Sandstones and relatively pure limestones are recrystallised, whereas aluminous lithologies, such as shales, develop (new) contact metamorphic mineral assemblages. In extreme cases, country-rocks adjacent to sill margins have been thermally metamorphosed to the extent that they started to melt, or fuse, and, upon cooling, form sheets or discrete masses of glassy material, now partially devitrified, referred to as buchites (Figure 8-28;

Figure 8-29:). Where these conditions of extreme temperature led to pyrometamorphism and, given an appropriately aluminous country-rock composition, minerals such as mullite, cordierite, sapphire and various Al-spinels formed.

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Isolated rafts of country-rock may also occur at internal contacts in the multiple sills. This material is thermally altered, ranging from mild 'baking' which involved recrystallisation and reduction in porosity, through to the formation of buchites where melting has occurred.

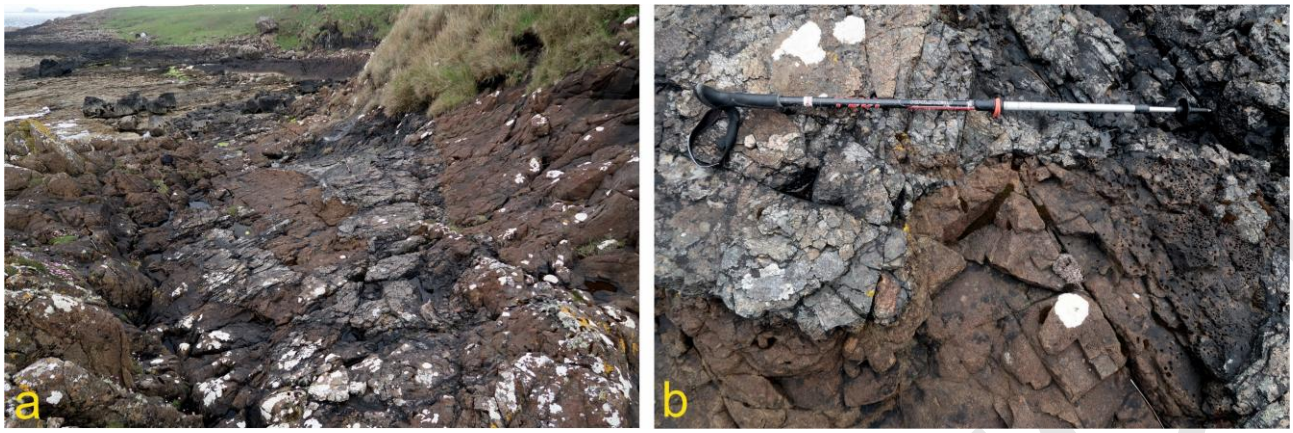


Figure 8-28: (a) A (grey) buchite formed by the pyrometamorphism of Middle Jurassic Duntulm Formation strata within the (orange) picrite sill north of Cairidh Ghlumaig, SW of Duntulm on Trotternish, Skye, pole *ca*. 1 m long; and, (b) detail of the contact between the picrite sill (orange) and a buchite (pale grey), note vesiculation of the sill (right-hand side), pole *ca*. 1 m long.



Figure 8-29: Buchite formed by the pyrometamorphism of folded Middle Jurassic Valtos Sandstone Formation strata (?), SE Hunish, below the Meall Tuath cliff, Trotternish, Skye. Coin *ca*. 24 mm across.

The olivine dolerite Elgol Sill, unrelated to the Little Minch Sill-complex, emplaced into the Middle Jurassic Garantiana Shale Member of the Bearreraig Sandstone Formation on Strathaird, has caused significant thermal alteration, evident in the field by its significant hardening of the shale when compared to other outcrops distant from any sills (Figure 8-30).

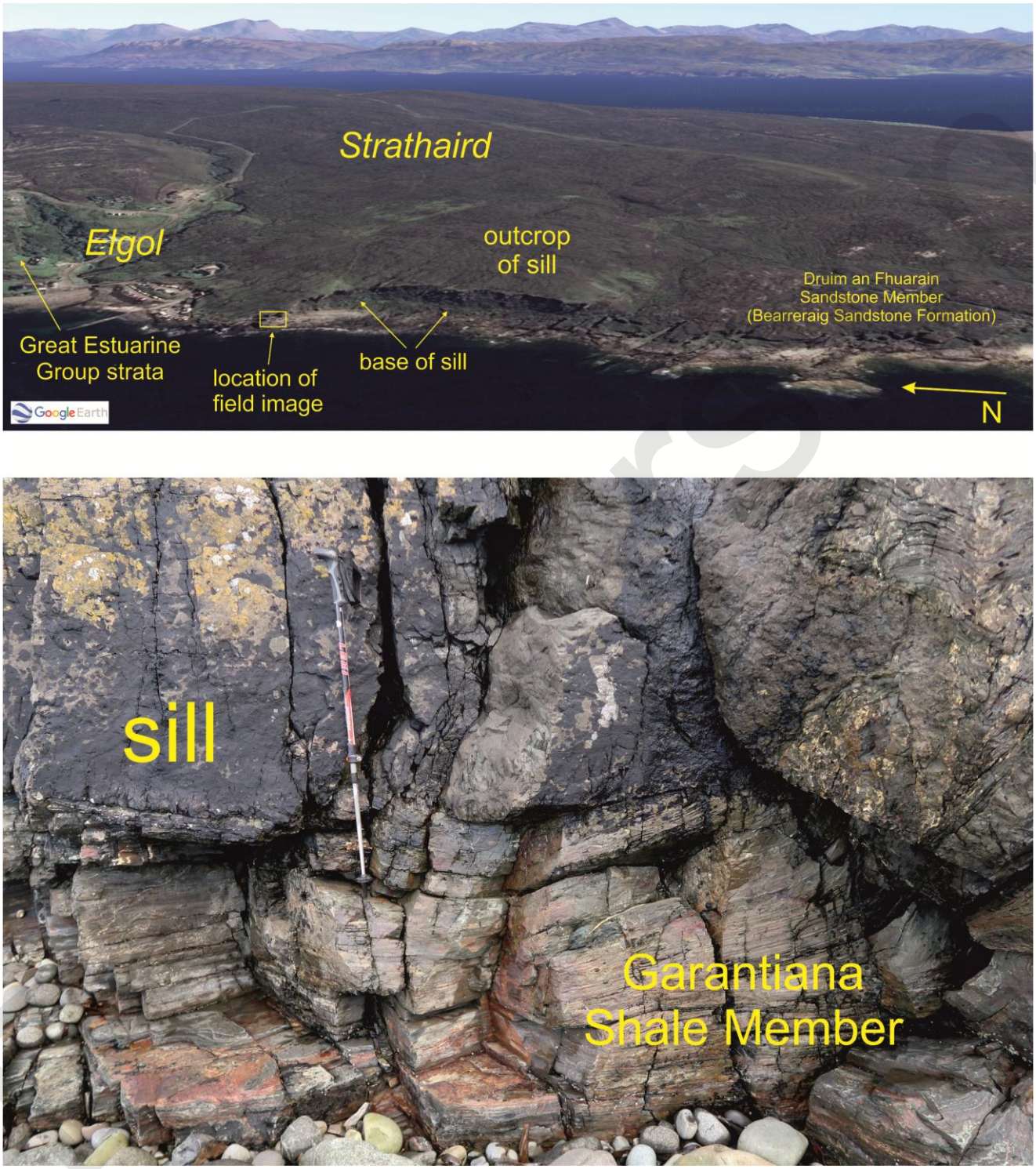


Figure 8-30: Oblique Google Earth© image of the Elgol Sill, Strathaird, Skye, and a field image of the base of the sill where in contact with thermally metamorphosed strata of the Garantiana Shale Member of the Bearreraig Sandstone Formation. Pole *ca*. 1 m long.

In common with exposures of picrite sills on Skye, for example at Duntulm and Rubha nam Brathairean, the Oskaig Sill on Raasay is, locally, significantly weathered and susceptible to erosion, producing olivine-rich sediment, locally pebbly (Walker 1932; Davidson 1933). Spheroidal (or onion skin/doleritic) weathering of these more olivine-rich sills is also relatively common (Figure 8-31). Where less weathered, it is evident that the Oskaig Sill has a layered character, similar to some of the sills on Skye.



Figure 8-31: Spheroidal (or onion skin/doleritic) weathering of the picrite sill on the east side of Rubha nam Brathairean, east Trotternish.

The geochemistry of the sills on Skye and the Shiant Isles and Skye has been investigated in order to understand their mode of emplacement and petrogenesis (Gibson 1990; Gibson & Jones, 1991; Foland *et al.* 2000; Henderson *et al.* 2000 and references therein (see Section 8.2.3)).

8.2.2 Field relationships and emplacement

Schofield *et al.* (2016) present an emplacement model for the Little Minch Sill-complex incorporating both onshore and extensive offshore data. Their high-resolution multibeam bathymetry and seismic reflection analyses reveal intricate intrusive morphologies - magma lobes, feeder dykes, and saucer-shaped sills - that were previously unrecognised from onshore exposures. Their findings suggest that basin-bounding faults played a less dominant role in magma transport than once thought. Integrating these offshore insights with existing onshore geology, they propose a new, more comprehensive framework for how this sill-complex was emplaced across the Sea of Hebrides Basin.

Faulting and tilting affect the outcrop pattern of the sill-complex, although it is likely that it was originally relatively flat lying to gently synclinal. Apparent sill transgressions are common, for example along the east coast of Trotternish from the Kilt Rock at Loch Mealt, south to Rubha nam Brathairean (‘Brother’s

Point'). The Trotternish sills typically dip towards the west and transgress up-sequence from south (within the Middle Jurassic Bearreraig Sandstone Formation) to north (within the Upper Jurassic Staffin Shale Formation). Only rarely do parts of the sill complex invade the overlying lavas, for example, at Oisgill Bay, on the west coast of Duirinish (Figure 8-13), and on Raasay, north of Dùn Caan.

Schofield *et al.* (2016)'s sill emplacement model comprises key stages, involving vertical inflation of the host rocks as magma propagates through it. Segments of the sill-complex merge with increased magma flux, producing so-called bridges and broken bridges (Figure 8-32). Based upon evidence at Rubha nam Brathairean on the east coast of Trotternish, where inclined rafts of Middle Jurassic Lealt Shale Formation strata separate picrodolerite sills at different stratigraphic levels (Figure 8-33), it is concluded that a bridge has formed in response to magma emplacement. The long axis of the bridge structure (NW-SE) is orthogonal to the inferred axis of magma emplacement (NE-SW).

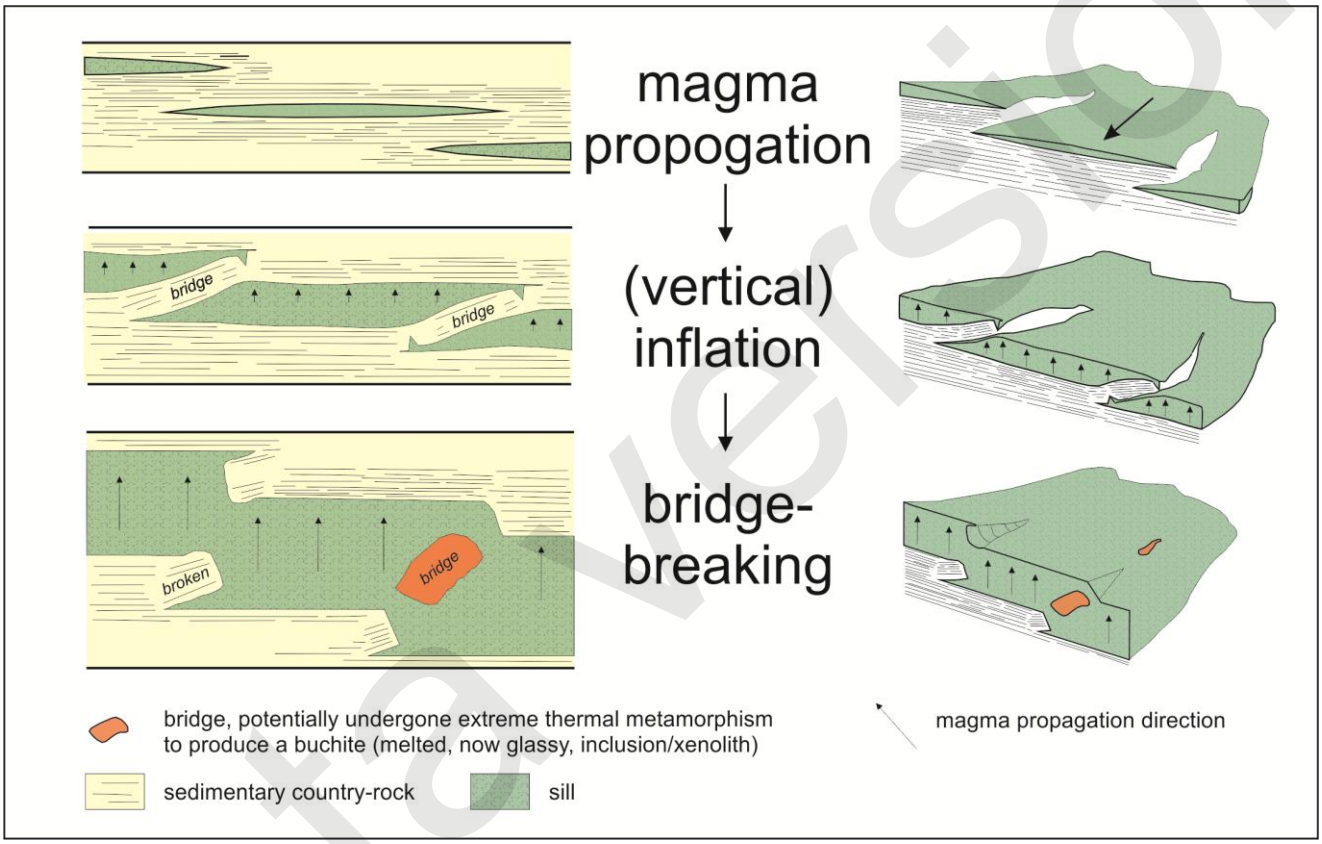


Figure 8-32: The development of bridge and broken bridge structures in sills (after Schofield et al. 2016).

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Figure 8-33: Complex relationships between sills and Lealt Shale Formation strata in coastal section south of Rubha nam Brathairean, Trotternish. Sills with green tint, largest exposure indicated, S.

From the high ground of Dùn Hasan at Rubha nam Brathairean, there is an instructive view, NW across Sgeir Gharbh to Port Earlish, of sill-country-rock (Lealt Shale Formation) relationships, comprising six sites on the coastline (Figure 8-34; Figure 8-35). Details are provided in the captions accompanying Figures 8.22 -8.31 (Figure 8-36; Figure 8-37; Figure 8-38; Figure 8-39; Figure 8-40; Figure 8-41; Figure 8-42; Figure 8-43; Figure 8-44; Figure 8-45)

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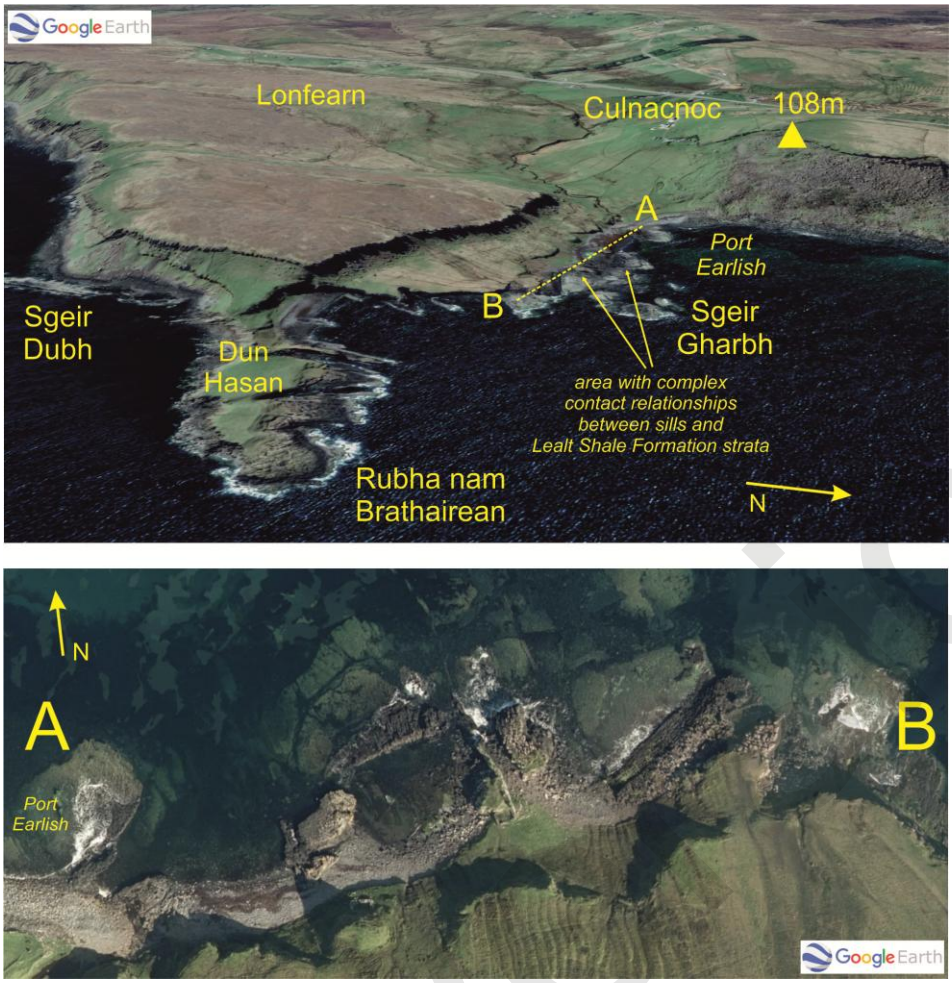


Figure 8-34: Annotated Google Earth® images for Rubha nam Brathairean (Brothers' Point).

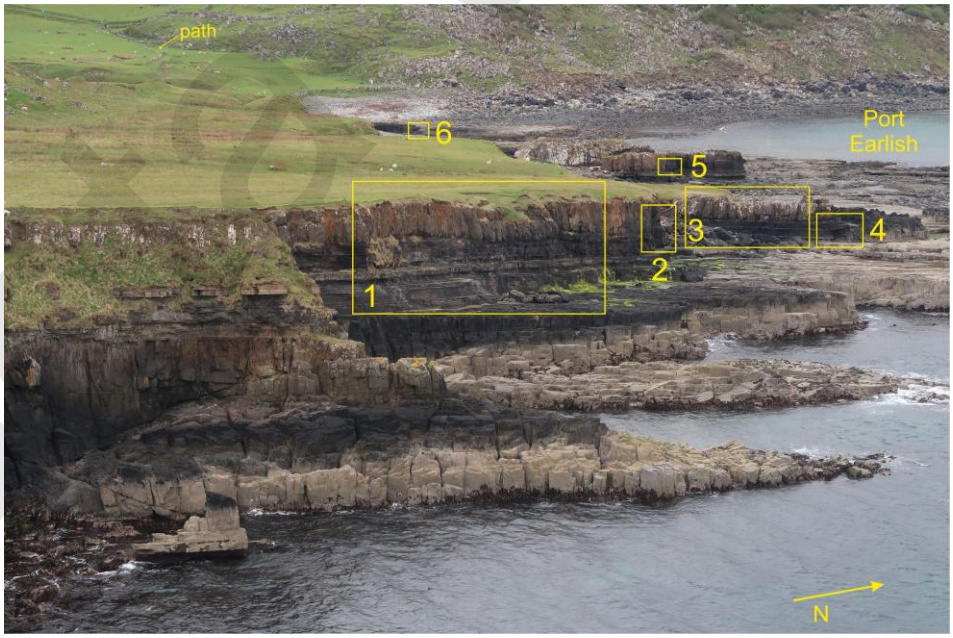


Figure 8-35: View west from Dùn Hasan to Sgeir Gharbh and Port Earlish, indicating key sites illustrating the inter-relationships between dolerite sills and their country-rocks (Lealt Shale Formation) strata.

Site 1:

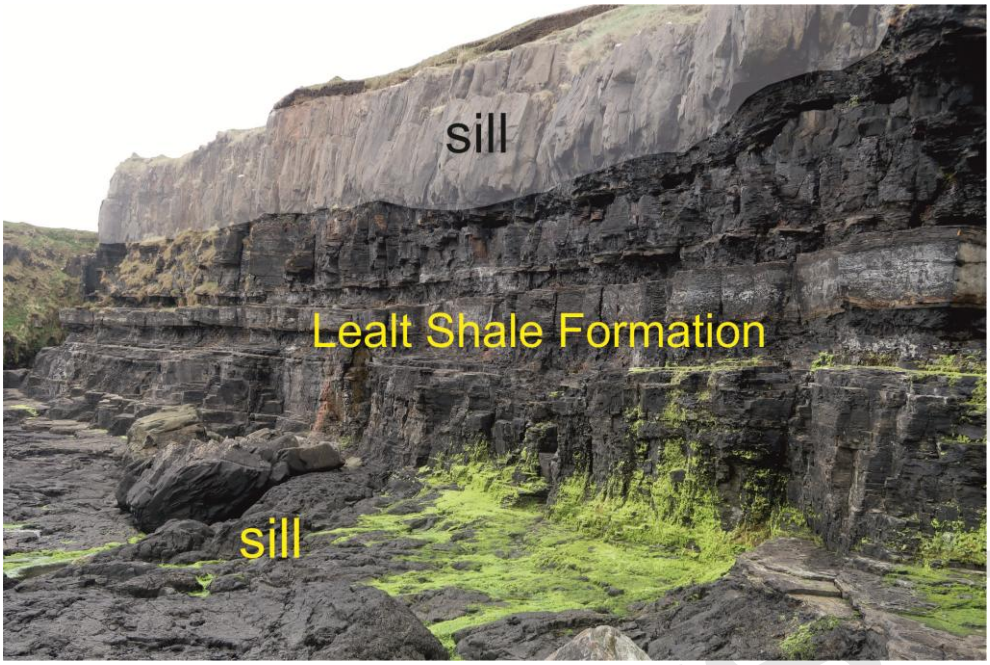


Figure 8-36: Horizontal, interbedded, lagoonal shales and limestones, capped by a bedding-parallel dolerite sill with well-developed prismatic joints. A classic sill and country-rock relationship.

Site 2:



Figure 8-37: Leading edge of a (colourised) sill injected into country-rock strata, prising a bedding surface open. This occurs during the initial stage of magma propagation and is referred to as a 'bridge.' Further injection will cause the country-rocks above the leading edge of the sill to become isolated (at least in 2D, and most likely in 3D) – a 'broken bridge'.

Brochure version

Site 3:



Figure 8-38: A bedding-parallel sill with vertical prismatic joints along most of the exposure. At the left-hand-end of the exposure, the cooling joints are inclined, inferring it is transgressive, i.e. cutting through bedding surfaces.

Site 4:

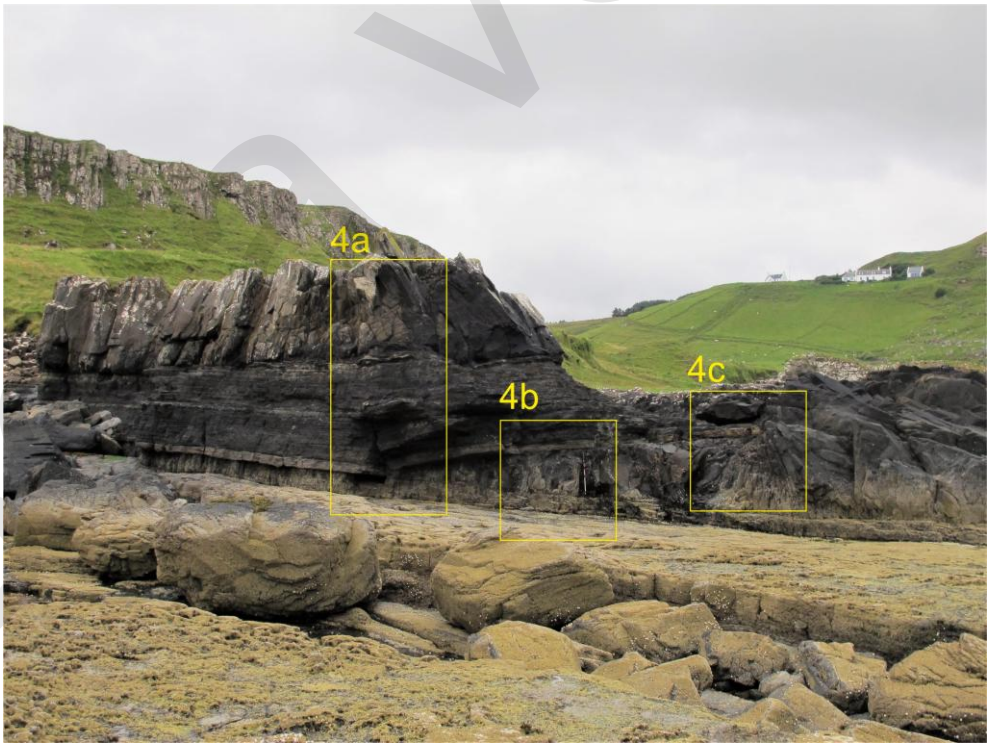


Figure 8-39: General view of Site 4 (see below). Pole *ca*. 1 m long.

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Site 4a:

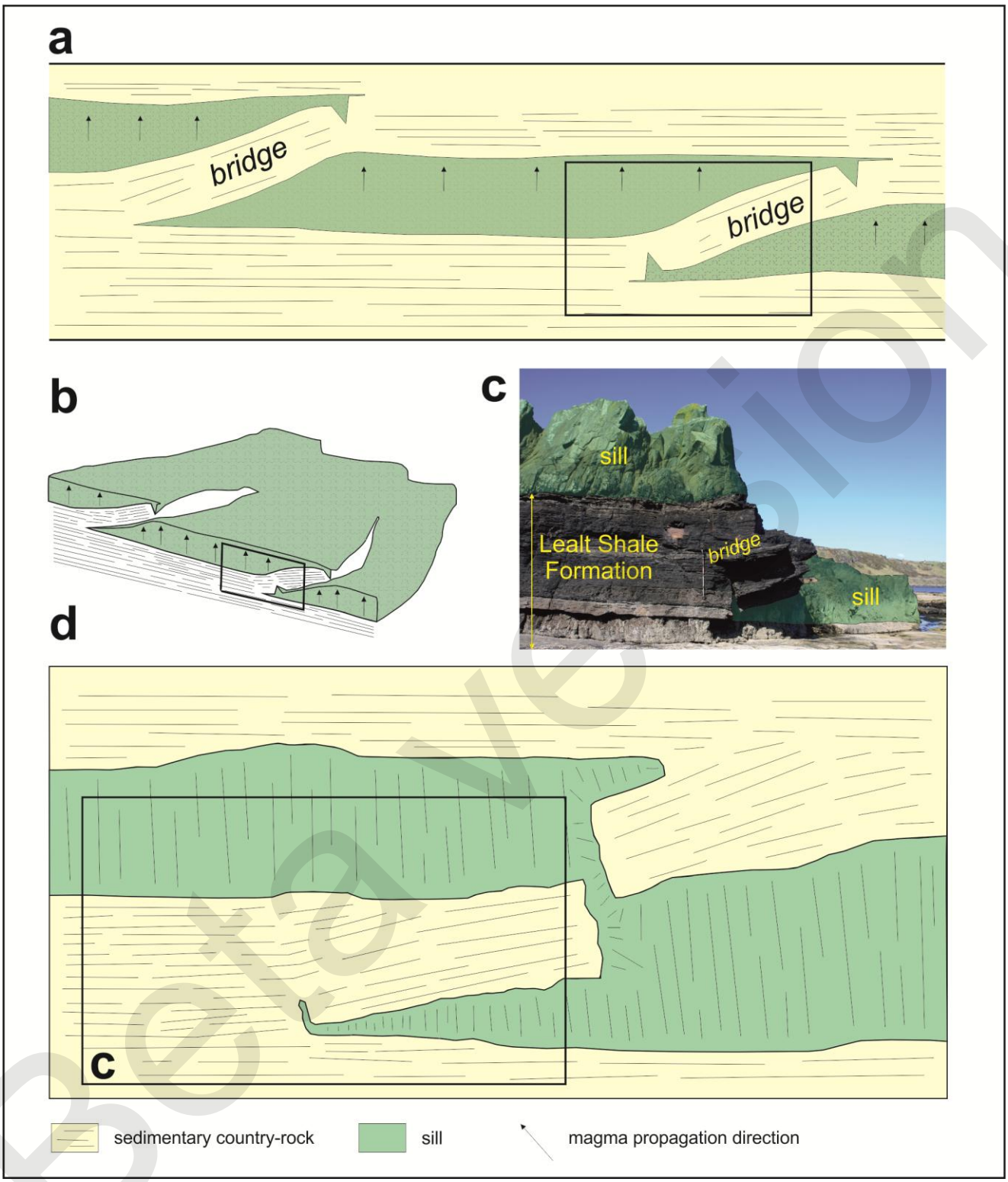


Figure 8-40: (a) & (b) Schematic diagrams illustrating mechanism of magma propagation and sill development (after Schofield *et al.* 2016); and, (c) & (d) example of a tensile cross fracture within Middle Jurassic Lealt Shale Formation strata intruded by an apophysis of an olivine dolerite sill during propagation/inflation process, Sgeir Gharbh, pole *ca.* 1 m long.

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Site 4b:



Figure 8-41: Tilting of the country-rock strata due to injection of magma along a bedding surface. The thicker the sill, the greater the dip of the country-rock strata, unless, as is the case here, a tensile fracture develops in the country-rocks. Pole *ca*. 1 m long.



Figure 8-42: A fracture within the country-rock shales above the leading edge of a sill. The country-rocks at the right-hand-end of the section are inclined due to the greater thickness of sill, below. Magma was also injected into the vertical (tensile) fracture. Pole *ca*. 1 m long.

Site 4c:



Figure 8-43: Country-rock limestones and shales terminating where enveloped by magma/sill. Such a feature is referred to as a 'broken bridge' in the sense that the country-rocks initially formed a bridge between the top and the bottom of the sheet(s) of magma that has been emplaced. Pole *ca*. 1 m long.

Preview

Site 5:



Figure 8-44: Minor discordance of sill with country-rock shales, with the sill locally forming bulbous projections into the country-rocks. Pole *ca*. 1 m long.

Site 6:



Figure 8-45: Two sill lobes (left and right of view), with an intervening bridge of inclined, stratified country-rocks. Pole *ca*. 1 m long (placed on left-hand lobe).

Preview

Further north, between the Kilt Rock at Loch Mealt and Dùn Dearg, Middle Jurassic Valtos Sandstone Formation strata act as a host to sills. Here, the sills, some tens of metres thick, are generally concordant to bedding. Schofield *et al.* (2016) identify various step-like features, bridges, broken bridges and rafts of country-rock strata that segment and complicate the sill outcrop pattern (Figure 8-20; Figure 8-21). They propose that this N-S coastal section is orthogonal to the axis of magma emplacement (E-W). In this section, multiple sills are common, with clear-cut internal contacts, indicative of multiple magma emplacement events, albeit not necessarily separated by substantial time intervals. Schofield *et al.* (2016) conclude that the sill complex at this locality developed by pulsed injection of laterally restricted sheets of magma parallel to the stratification of the host-rocks at different stratigraphic levels, which subsequently merged, or almost merged.

At Staffin Harbour, sills occur at two stratigraphic levels within Middle Jurassic Great Estuarine Group strata, a lower unit within the Duntulm Formation and an upper unit within the Kilmaluag Formation (Figure 8-46; Figure 8-47). Here, the upper surface of the Staffin Slipway sill is exposed and preserves flow indicators in the form of ropey structures and stretched and aligned vesicles. Schofield *et al.* (2016) interpret the gross morphology of the upper sill, which forms highs along the cliff line, as evidence for a large-scale, finger-like geometry.

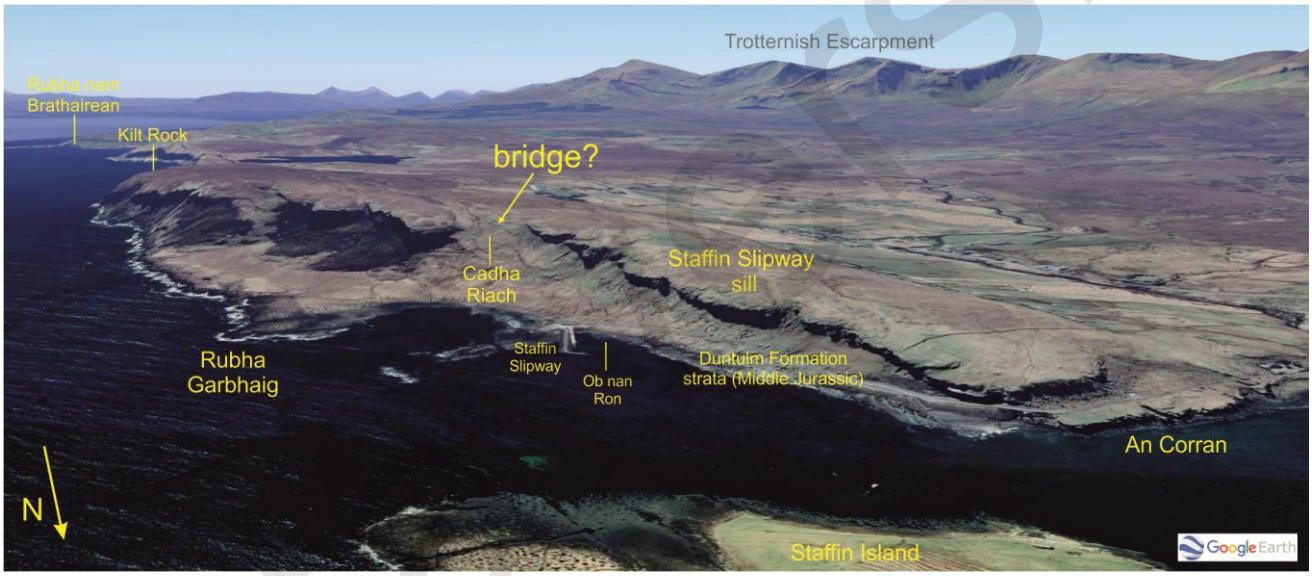


Figure 8-46: Oblique Google Earth© image of the coastline between An Corran and the Staffin slipway at Ob nan Ron, Trotternish. The inland cliff is composed of a crinanite sill intruded into Middle Jurassic Duntulm Formation strata (exposed on the shore). View towards the south.

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Figure 8-47: Field image of the prismatic-jointed Staffin Slipway sill, viewed from the slipway towards the west. Height of cliff *ca*. 70 m.

At Neist Point (Rubhan a h-Eist) on the west coast of Duirinish, Skye, a thick olivine dolerite sill forms the prominent cliffs upon which the Stevenson-designed lighthouse is located (Figure 8-50). South of the Point, in Moonen Bay, Middle Jurassic Lealt Shale Formation strata, inclined at *ca*. 40°, form a large bridge, up to 40 m across, separating two leaves of the sill complex (Figure 8-51). The bridge structure is further affected by irregular dyke-like masses of olivine dolerite. Schofield *et al*. (2016) interpret these dyke-like intrusions as evidence of magma invading fractures as the country-rock strata was inflated during sill emplacement, bridge development, and subsequent deformation of the bridge.



Figure 8-48: The Neist Point Sill forming the west-facing cliffs between the prow of An t-Aigeach ('The Stallion') and Neist Point (with lighthouse).

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Figure 8-49: The Neist Point Sill forming the west-facing cliffs between the prow of An t-Aigeach ('The Stallion') and Neist Point (with lighthouse).



Figure 8-50: (a) The Neist Point Sill viewed towards the SSW from the coastal cliffs. The prow of An t-Aigeach ('The Stallion') has a height of *ca*. 90 m above sea level. The top of the olivine dolerite sill is locally preserved, seen at the far left of the cliff line, where (inaccessible!) hornfelsed, flat-lying Middle Jurassic Lealt Shale Formation strata are preserved. The sill has a complex, irregular set of prismatic joints; and, (b) detail of Lealt Shale Formation strata above sill.

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Figure 8-51: Irregular top of the olivine dolerite sill forming Sgeir nan Sìdhean, east of Neist Point in Moonen Bay, Duirinish, Skye. The sill is intruded into horizontally bedded Middle Jurassic Lealt Shale Formation and overlying Valtos Sandstone Formation strata. View towards the SE.

8.2.3 The Shiant Isles sill(s)

The Shiant Isles, located between Trotternish on Skye and Harris in the Outer Hebrides, is the most studied group of outcrops of the Little Minch Sill-complex. The various intrusions that form the three main islands provide a wealth of data concerning the nature, origin and evolution of the magmas involved, together with the types of processes involved in their formation. Below is set out the key observations and interpretations that have been made in recent times, specific to the Shiant Isles sills, which build upon the original investigations of Walker (1930) and Drever (1953), by Gibb & Henderson (1996) and Holness *et al.* (2017, 2022). A more general account of the compositional characteristics of the Little Minch Sill-complex is presented in Section 8.2.4.

The Shiant Isles comprises three main islands - Garbh Eilean and Eilean an Taighe, joined in tombolo-fashion, and Eilean Mhuire - together with a string of small, E-W-aligned group of islets, the Galtachan (Figure 8-52; Figure 8-53; Figure 8-54; Figure 8-55; Figure 8-56; Figure 8-57; Figure 8-58; Figure 8-59; Figure 8-60; Figure 8-61; Figure 8-62; Figure 8-63).

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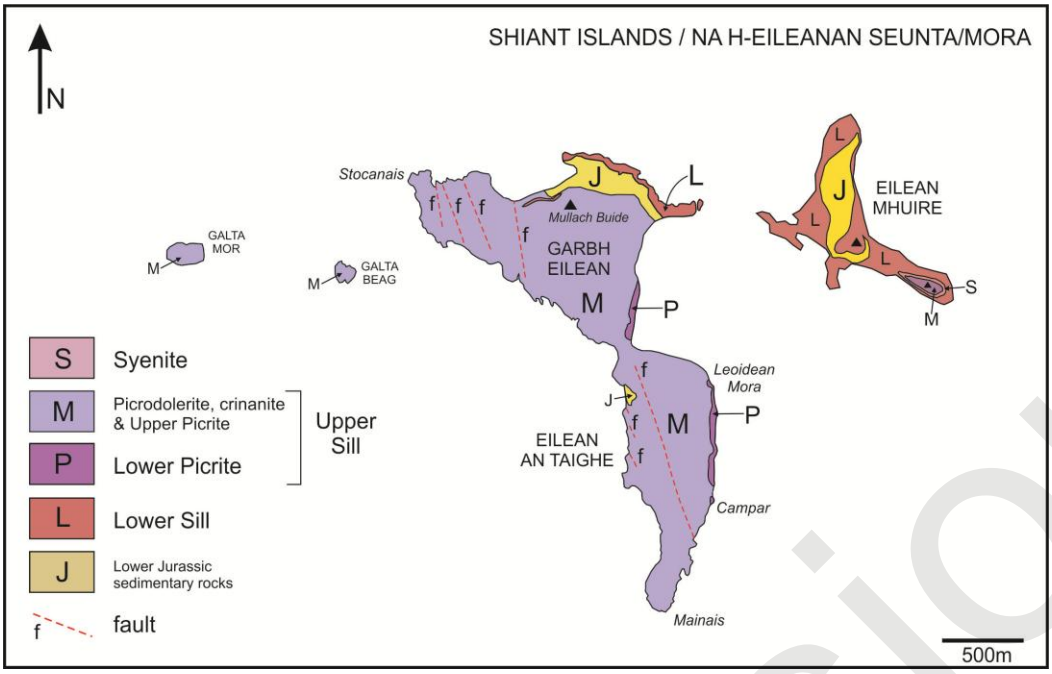


Figure 8-52: Simplified geological map of the Shiant Isles (based on Walker (1930) and Gibb & Henderson (1996)).



Figure 8-53: Oblique Google Earth© images of the Shiant Isles, viewed NW towards Harris and Lewis, and SE towards Trotternish, north Skye.

Beta version



Figure 8-54: The Shiant Islands, viewed from Harris towards Trotternish, Skye.



Figure 8-55: The Shiant Islands, viewed from Rubha Hunish, north Trotternish, Skye, towards Harris.



Figure 8-56: Eilean an Taighe (left) and Garbh Eilean (right) joined by a tombolo, viewed towards the SW.



Figure 8-57: Eilean an Taighe, viewed towards the west. [Photograph courtesy of Ian Williamson]

Beta version



Figure 8-58: The west-facing cliffs of north Eilean Mhuire. [Photograph courtesy of Ian Williamson]



Figure 8-59: The north-facing cliffs of central Garbh Eilean. [Photograph courtesy of Ian Williamson]



Figure 8-60: Eilean an Taighe viewed towards the south, across the tombolo at Mol Mòr from Garbh Eilean.

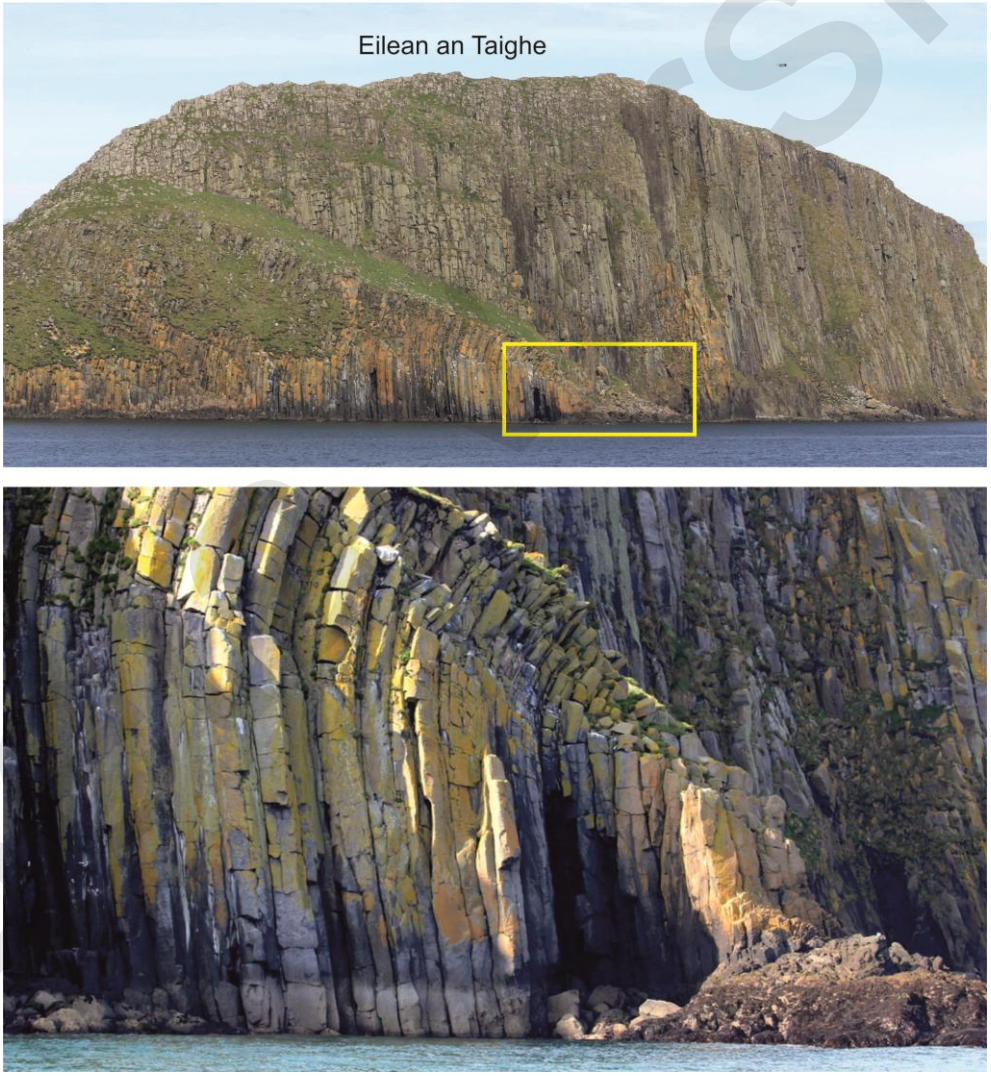


Figure 8-61: The east-facing cliffs of Eilean an Taighe.

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Figure 8-62: Eilean an Taighe (left) and Garbh Eilean (right) viewed towards the NW.



Figure 8-63: Central east Garbh Eilean viewed towards the west.

The Shiant Isles Main Sill is a composite igneous body *ca*. 165–168 m thick, comprising at least four discrete intrusions. An early *ca*. 24 m-thick picrite sheet forms the base; overlain by a *ca*. 135 m-thick picrodolerite/crinanite unit (PCU), itself subdivided into basal (*ca*. 22 m) and upper (2 m) parts, separated by internal contacts (Gibb & Henderson 1996; Holness *et al*. 2017; Holness *et al*. 2022).

From base to top, Gibb identified the following key features in the sill: (a) a chilled basal contact against Jurassic sedimentary rocks ('olivine teschenite'); (b) early picritic cumulates with abundant olivine and crystal lamination (*ca*. 24 m thick); (c) a sharp transition to intrusive picrodolerite sheets; (d) a thick central

picrodolerite/crinanite unit (PCU), comprising multiple intrusive leaves with grain-size variations (*ca.* 135 m thick, with basal (*ca.* 22 m) and upper (2 m) parts, separated by internal contacts); (e) a complex roof facies with various leaves, including an olivine teschenite chilled sheet, below thermally altered ('baked') Jurassic sedimentary rocks; and, (f) late syenitic segregations in the upper levels. Significantly, columnar joints 'ignore' these internal contacts (Figure 8-64).

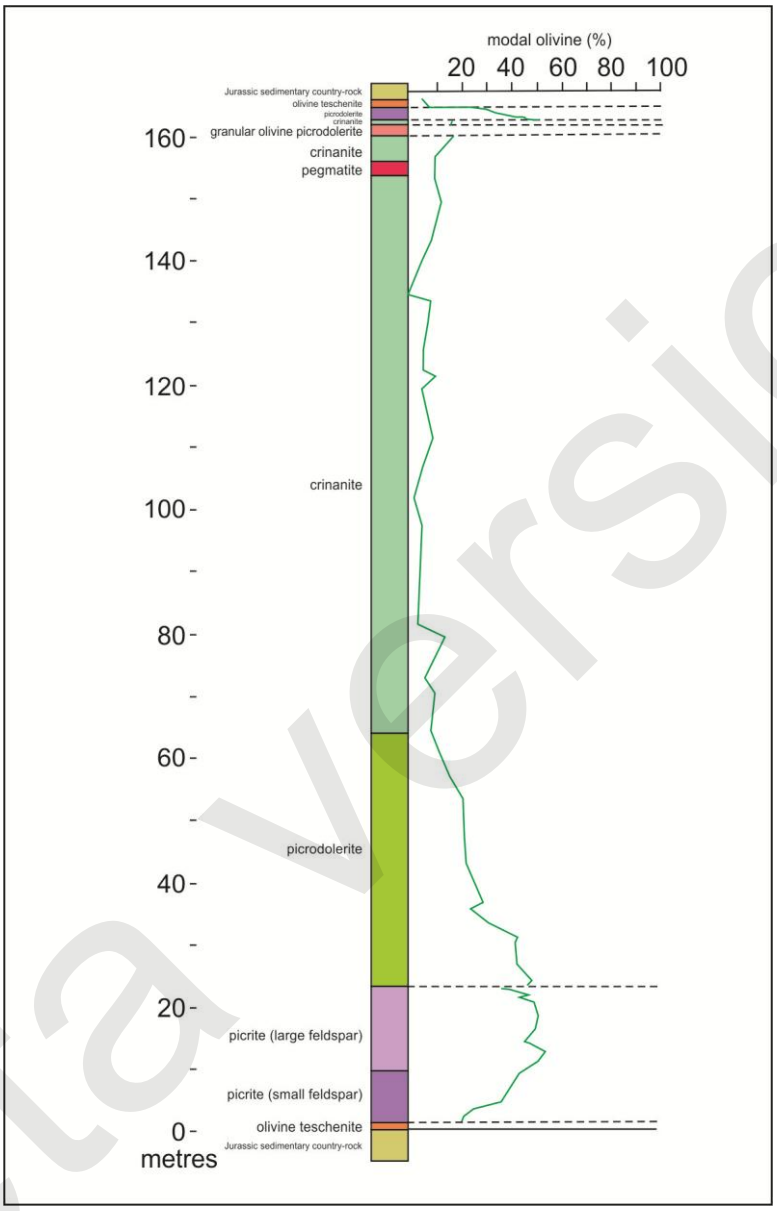


Figure 8-64: Detailed composite log with lithology data and olivine percentage data for the Shiant Isles sill (after Gibb & Henderson 1996).

Sharp paired chemical and textural breaks coincide with these intrusive contacts: each new pulse shows abrupt transitions in mineralogy, crystal size, and texture, confirming a multi-phase emplacement model (Gibb & Henderson 1996; Gibb & Henderson 2006). Whole-rock data support this model, with olivine, clinopyroxene and plagioclase compositions reflecting nearly perfect fractional crystallization.

Compositional zoning in clinopyroxene crystals demonstrates a distinctive calcic-augite-hedenbergite trend in Ca-Mg-Fe space - a pattern separate from the standard tholeiitic or alkaline fractionation trends - and indicative of mildly alkaline basalt magmas. Gibb (1973) also noted that Al, Ti, and Na contents in

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these pyroxenes correlate with fractionation and magmatic oxidation state, which is interpreted as reflecting magma chemistry and H_2O-controlled oxygen fugacity during crystallization.

Holness *et al*. (2017) used microstructural metrics to reveal dynamic behaviour during solidification. In the central picrodolerite-crinanite unit (CPU), olivine crystal size decreases upwards in the lower section (*ca*. 10 m), then coarsens upward through *ca*. 50 m - an inverse size zoning attributed to crystal settling followed by crystal growth in a convecting magma. Complementary coarsening-downwards sequences at the roof reflect convective overturn, rather than static cooling.

Holness *et al*. (2022) further quantified dihedral angles at clinopyroxene-plagioclase-plagioclase junctions and plagioclase aspect ratios. Observed values align with theoretical predictions for a sill *ca*. 135 m thick, supporting their proposed sill geometry and thermal evolution.

Nd and Sr isotopic analyses across a vertical section through the composite sill show systematic variations consistent with multiple intrusions and limited crustal contamination. Whole-rock initial $^{87}Sr/^{86}Sr$ values range from 0.7037 to 0.7061 and $^{143}Nd/^{144}Nd$ (ε_{Nd}) values from –0.7 to +5.7, reflecting a combination of magmatic pulses and minor assimilation, with interstitial and hydrothermal modifications (Foland *et al*. 2000).

In summary, emplacement of the Shiant Isles Sill involved multiple intrusive pulses to build the composite intrusion, including a basal picrite unit overlain by a thick picrodolerite/crinanite unit (PCU) with sharp internal boundaries. Mineral zoning (olivine, clinopyroxene, plagioclase) indicates an efficient alkaline fractional crystallization trend. Textural and microstructural data denote two-stage crystal settling and crystallization under convection, confirmed by crystal-size trends and dihedral-angle/aspect-ratio measurements matching modelled sill thickness. Nd–Sr isotopic systematics indicate the role of distinct pulses with modest crustal interaction and post-magmatic modification.

8.2.4 Raasay

On the west coast of Raasay, between Oskaig Point and Eilean Aird nan Gobhar, a multi-leaved sill with units composed of all of the main compositional types is exposed (Figure 8-65; Figure 8-66; Figure 8-67; Figure 8-68); inland exposure is poor, and the eastern margin of the outcrop is interpreted as a fault against Middle Jurassic Bearreraig Sandstone Formation strata and the Raasay Granite Sill (BGS 2006a).



Figure 8-65: The Oskaig Sill, forming the promontory of Oskaig Point, SW Raasay.

Beta version



Figure 8-66: The Oskaig Sill on the west coast of Raasay, forming the promontory of Oskaig Point, is a multiple intrusion with leaves of the main compositions (picrite, picrodolerite, olivine dolerite and crinanite), with well-developed, near-vertical prismatic joints. View towards the west, with the east coast of north Skye in the distance. Sheep for scale.



Figure 8-67: Detail of the northern end of the Oskaig Sill, west coast of Raasay, forming the promontory of Oskaig Point.



Figure 8-68: Gabbro pegmatite within the Oskaig Sill. Ruler 30cm long.

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South and north of the highest point on Raasay, Dùn Caan, flat-lying sheets of dolerite and crinanite are interpreted as sills (Walker 1932; BGS 2006a) (Figure 8-69; Figure 8-70; Figure 8-71; Figure 8-72). The sill south of Dùn Caan is intruded along the unconformity between Middle Jurassic Lealt Shale Formation strata and the Upper Cretaceous Morvern Greensand Formation, whereas those to the north are interpreted to been intruded into an outlier of the Paleocene Skye Lava Field.



Figure 8-69: View towards the south from the summit of Dùn Caan on Raasay, with the elongate Loch na Mna on the west (right) side of the view. The rugged crags immediately below, with the associated boulder scree, is the outcrop of a flat-lying multiple olivine dolerite sill intruded into poorly exposed Middle Jurassic Lealt Shale Formation strata.



Figure 8-70: Profile view, towards the east, of prismatic-jointed dolerite sill (lower terrace, right-hand-side) and lavas forming the summit of Dùn Caan, Raasay.

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Figure 8-71: Profile view, towards the east, of prismatic-jointed dolerite sill south of Dùn Caan, Raasay.



Figure 8-72: Detail of prismatic-jointed dolerite sill south of Dùn Caan, Raasay. Pole *ca.* 1 m long.

Preview

A banded dyke, with many features in common with the sills, has been briefly described from Dùn Bornesketaig, near Kilmuir on the west coast of Trotternish, Skye, by Drever (1969) (Figure 8-73; Figure 8-74). It has a N-S trend, is *ca*. 1.5 m wide, and can be traced along trend for *ca*. 60 m. Parallel to the dyke margins are alternating bands dominated by (dendritic-textured) olivine and augite. A zeolite-rich central portion of olivine dolerite is particularly obvious (Figure 8-74). Its location, within the outcrop area of the Little Minch Sill-complex, suggests a genetic relationship, involving some form of flow differentiation mechanism of formation.



Figure 8-73: The N-S -trending banded/layered dyke on the shore west of Dùn Bornesketaig, NW Trotternish, Skye, comprising alternating bands of dendritic olivine and augite. Pole *ca*. 1 m long.



Figure 8-74: Detail of the N-S -trending banded/layered dyke on the shore west of Dùn Bornesketaig, NW Trotternish, Skye, comprising the central zeolitised olivine dolerite portion. Ruler 30 cm long.

8.2.5 The Magmatic Evolution of the Little Minch Sill-complex

Walker (1932), Anderson & Dunham (1966) and Gibson & Jones (1991) identify five distinct rock compositions of sills (or leaves, or units) within the sill complex: (1) olivine dolerite (for example, the sill at the Loch Mealt waterfall, the so-called Kilt Rock); (2) marginal tachylitic and crystalline basaltic variants (for example, the upper contact of the lower sill at Rubha Hunish); (3) picrite (40-60% olivine) and picrodolerite (10-20% olivine) (for example, Ru Bornesketaig, Kilmuir); (4) crinanite (analcime-bearing alkali basalt/dolerite) and teschenite (alkaline basalt/dolerite with less than 5% olivine) variants (for example, the lower sill at Rubha Hunish and the sill at Tulm Bay, north of Duntulm); and, (5) pegmatites, dominated by clinopyroxene and plagioclase, within the dolerites (for example, the Kilt Rock Sill and the Oskaig Sill) and within many of the picrite and picrodolerite sills.

All five rock-type groups contain varying amounts of: forsteritic olivine (*ca*. Fo_{80}), diopsidic augite, calcic plagioclase (*ca*. An_{60-30}), chrome-spinel, Fe-Ti oxides and zeolites (analcime and thomsonite). Where augite and plagioclase dominate, the rock-types are (1) and (2), grading into (3) with higher olivine content, and (4), where zeolites become significant. The development of (5) appears to have been more specific, being dependent upon the build-up of volatiles during late-stage crystallisation processes.

Walker (1932) suggested that variations in composition throughout the sill complex could be attributed to *in situ* crystal-liquid fractionation by gravitational settling of early precipitated crystals. However, Anderson & Dunham (1966) concluded that there is little good mineralogical and textural evidence for this model, although they do propose that the variations in mineralogy between individual sills throughout the district may be the result of such processes having operated in a magma chamber (but with no direct evidence of its existence) at depth.

In a subsequent re-investigation of these associations, Simkin (1967) proposed that some form of flow differentiation process has taken place. As magma was injected along flat-lying fissures, phenocrysts would move towards the centre of the conduit and there would be rapid chilling of magma at the fissure margins, resulting in the tachylitic and basaltic marginal facies of some sills. The porphyritic magma within the central portion of the conduit, when spreading out laterally, would be influenced by gravity and hence facilitate the formation of olivine cumulates (i.e. the picrites and picrodolerites).

Gibson & Jones (1991) concluded that the textural characteristics of the graded layers indicate that much, if not all, of the crystallisation was *in situ*, with no field-scale or microscopic textural evidence for crystal-settling processes. Cryptic mineral variation has not been recognised. Most of the recognised mineral textures, such as elongate plagioclase crystals and swallow-tail terminations of clinopyroxene crystals, indicate rapid cooling and crystal growth. As relatively rapid cooling of individual units occurred, the large thermal contrast between each unit and its country-rocks (either Jurassic strata or previously crystallised sills) would have significantly influenced the order of formation and the textural characteristics of the crystallising minerals. As certain minerals crystallised, for example olivine and clinopyroxene, the magma would be depleted in the components needed for their formation, ultimately (but) temporarily halting their precipitation and causing plagioclase to crystallise. This cycle of selective crystallisation would repeat, resulting in the many mineralogically-graded layers preserved in certain sills.

Gibson & Jones (1991) deduced that the parental magma was of alkali olivine basalt composition, with *ca*. 10% MgO. Fractionation occurred at relatively shallow depths, and batches of the three main magma compositions (picrite, picrodolerite and alkali olivine-dolerite) were then tapped from the processing chambers and emplaced at shallow levels as sills. The most primitive melt, which formed the picrites, carried chrome-spinel, olivine and plagioclase prior to emplacement. The similarity of olivine

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compositions in different lithologies, for example the picrites and the crinanites, suggests that they may have a common source and have not necessarily crystallised as part of the intrusion in which they occur.

During emplacement, flow differentiation was a significant process close to the margins of the sills, whereas relatively late-stage filter pressing yielded various pegmatite sheets. The chilled margins to the sills are typically contaminated by country-rock mudstone and sandstone.

Pegmatites and localised veins are interpreted as the products of relatively late-stage interstitial melts that have amalgamated by some form of filter-press mechanism involving (gravity-driven) compaction, as they are expelled from the dominant, already-crystallised crystal framework of the cooling sills (Figure 8-75; Figure 8-76). Low-temperature late-stage minerals, such as zeolites, formed in response to elevated H_2O contents.



Figure 8-75: Near-horizontal gabbro pegmatite layers in the picrite sill north of where the Lealt River enters the sea at Inver Tote on the east coast of Trotternish, Skye. The main minerals within the pegmatite are clinopyroxene and plagioclase. Pole *ca.* 1 m long.



Figure 8-76: An irregular patch of gabbro pegmatite within the Oskaig Sill on the west coast of Raasay, forming the promontory of Oskaig Point. Ruler 30 cm long.

Emplacement of the sills appears to have been a complex, discontinuous process (Gibson & Jones 1991; Holness *et al*. 2017). As magma was withdrawn from a deeper-level, compositionally zoned, storage and processing chamber, the rate of discharge may have been critical, with high discharge rates favouring olivine-rich magmas, i.e. with accumulative olivine. The field evidence suggests that such olivine-rich magma was withdrawn first from the chamber (or chambers) and emplaced as early picrite and picrodolerite sills. A reduction in the (magma) withdrawal rate would enable the ascent of the olivine-poor magmas that crystallised to form the olivine dolerite, crinanite and teschenite sills. Essentially, the picrites may represent magmas that have accumulated olivine, and the crinanites and teschenites represent magmas that have lost, or fractionated, olivine. The role of crystal setting is less clear and will be influenced by many factors, including: the percentage of phenocrysts in the magma, the rate of magma emplacement, the geometry (including thickness) of the sill; and, the rate of heat loss and crystallisation history of the magma.

From a mineralogical study of the sill(s) forming the Shiant Isles, Holness *et al*. (2017) concluded that a high crystal (olivine) content of a picritic sill magma stifles/inhibits crystal settling, whereas with olivine-porphyritic picrodolerite/crinanite sill magmas, significant olivine fractionation by crystal settling is possible.

Gibson (1990) provides further details of the geochemical evolution of the Little Minch Sill-complex. Similarities between the identified alkali olivine basalt parental magma (see above) and the parental magma(s) of the Skye Main Lava Series are noted (Chapter 10). The most compositionally evolved sills, the crinanites and teschenites, are the most (crustally) contaminated, as indicated by their disturbed radiogenic isotope signatures, involving the assimilation of amphibolite facies basement gneiss of the Lewisian Gneiss Complex during fractional crystallisation of the parental magma, so-called assimilation-during-fractional-crystallisation (or AFC).

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8.3 The Loch Scridain Sill-complex

The Loch Scridain Sill-complex intrudes the Moine Supergroup basement, the unconformably overlying Mesozoic sedimentary sequence, and the Paleocene lavas in SW Mull, particularly on the Ross of Mull and on the north side of Loch Scridain (Figure 8-77).

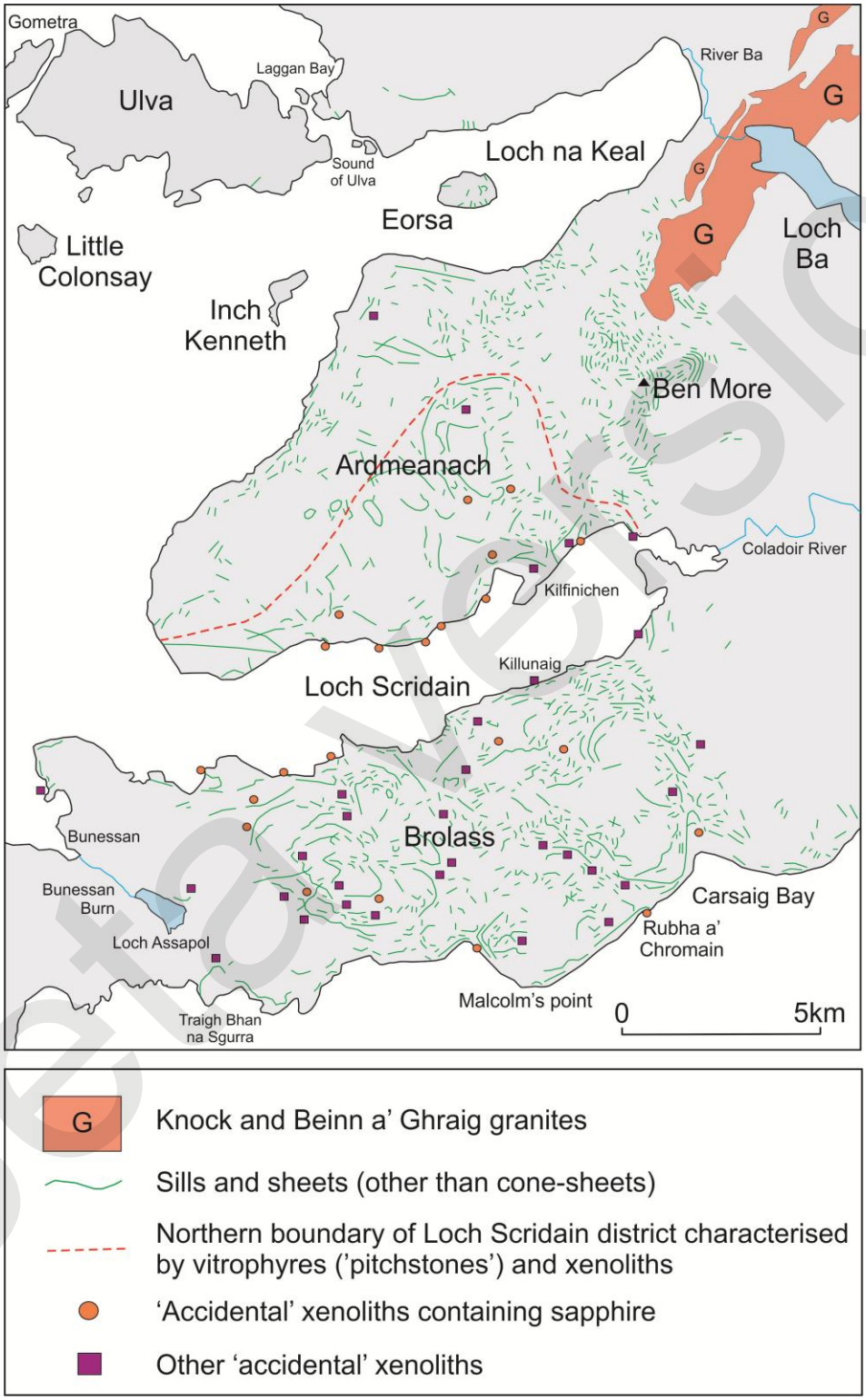


Figure 8-77: Distribution of the Loch Scridain Sill-complex, SW Mull (after Bailey *et al.* 1924).

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The sills are typically between 0.5 and 6 m thick, but exceptionally exceed 10 m, and commonly have well developed chilled margins. They are of tholeiitic affinity, ranging in composition from tholeiitic (MORB-like) basalt, through andesite and dacite, to rhyolite (including glassy variants). Basaltic compositions are the most common, with about 20 per cent of the intrusions being of intermediate composition, the product of the contamination of basaltic magma with silicic crustal melts, and a relatively small number of rhyolitic composition, predominantly the product of crustal melting. These intrusions may be related to the initial stages of the development of the Mull Central Complex (Centre 1 or Glen More Centre, Chapter 9).

The Loch Scridain sills may be divided into three distinct geochemical groups (Preston *et al*. 1998a; Chapter 10). The basic sills (Group 1) are markedly xenolithic (see below), containing both cognate and crustal types. The cognate xenoliths are typically coarse-grained and of ultrabasic and basic composition and most likely of cumulate origin (Preston & Bell 1997) (Figure 8-78). Group 2 are andesites and dacites formed by the interaction of Group 1 magma(s) with magma produced by melting of crustal lithologies, most likely pelites within the Moine Supergroup (Chapter 2). Group 3 are rhyolites, derived from the partial melting of pelitic units within the Moine Supergroup.

Many, but not all, of the sills are xenolithic (Figure 8-79; Figure 8-80), some only with cognate (mainly gabbro) material and many with accidental (upper crustal) material represented; two of the best examples of accidental xenolithic sills are at Killunaig and Kilfinichen Bay, on the south and north sides of Loch Scridain, respectively. Columnar joints are common in the less xenolithic sills (Figure 8-81; Figure 8-82; Figure 8-83; Figure 8-84).



Figure 8-78: Gabbro xenolith in the Kilfinichen (Chill Fhinichin) Sill, north side of Loch Scridain, SW Mull. Finger for scale. [Photograph courtesy of John Faithfull]

Pre-publication version



Figure 8-79: Highly xenolithic sill, Nuns' Pass, between Carsaig Bay and Malcolm's Point, south coast of Brolass, SW Mull.



Figure 8-80: Highly xenolithic sill, Kilfinichen (Chill Fhinichin), north side of Loch Scridain, SW Mull. [Photograph courtesy of John Faithfull]



Figure 8-81: The columnar-jointed Aird Ghlas Sill, west side of Carsaig Bay, south coast of Brolass. [Photograph courtesy of James Westland]



Figure 8-82: Detail of the columnar joints in the Aird Ghlas Sill, west side of Carsaig Bay, south coast of Brolass. [Photograph courtesy of James Westland]



Figure 8-83: Carsaig Arches, Malcolm's point, SW Mull, partly constructed of a non-xenolithic dolerite sill.



Figure 8-84: Prismatic-jointed, non-xenolithic, dolerite sill, east of Carsaig Arches, Malcolm's point, SW Mull, intruded into a columnar-jointed basaltic lava.

Composite sills occur, commonly involving crystalline and glassy rock types of significantly different compositions as in, for example, the classic xenolithic sill at Rudh' a' Chromain on the south coast of Brolass, which has a *ca*. 10 m thick central vitrophyre ('felsite') with upper and lower basaltic units (up to 2m thick) still preserved (Figure 8-85).

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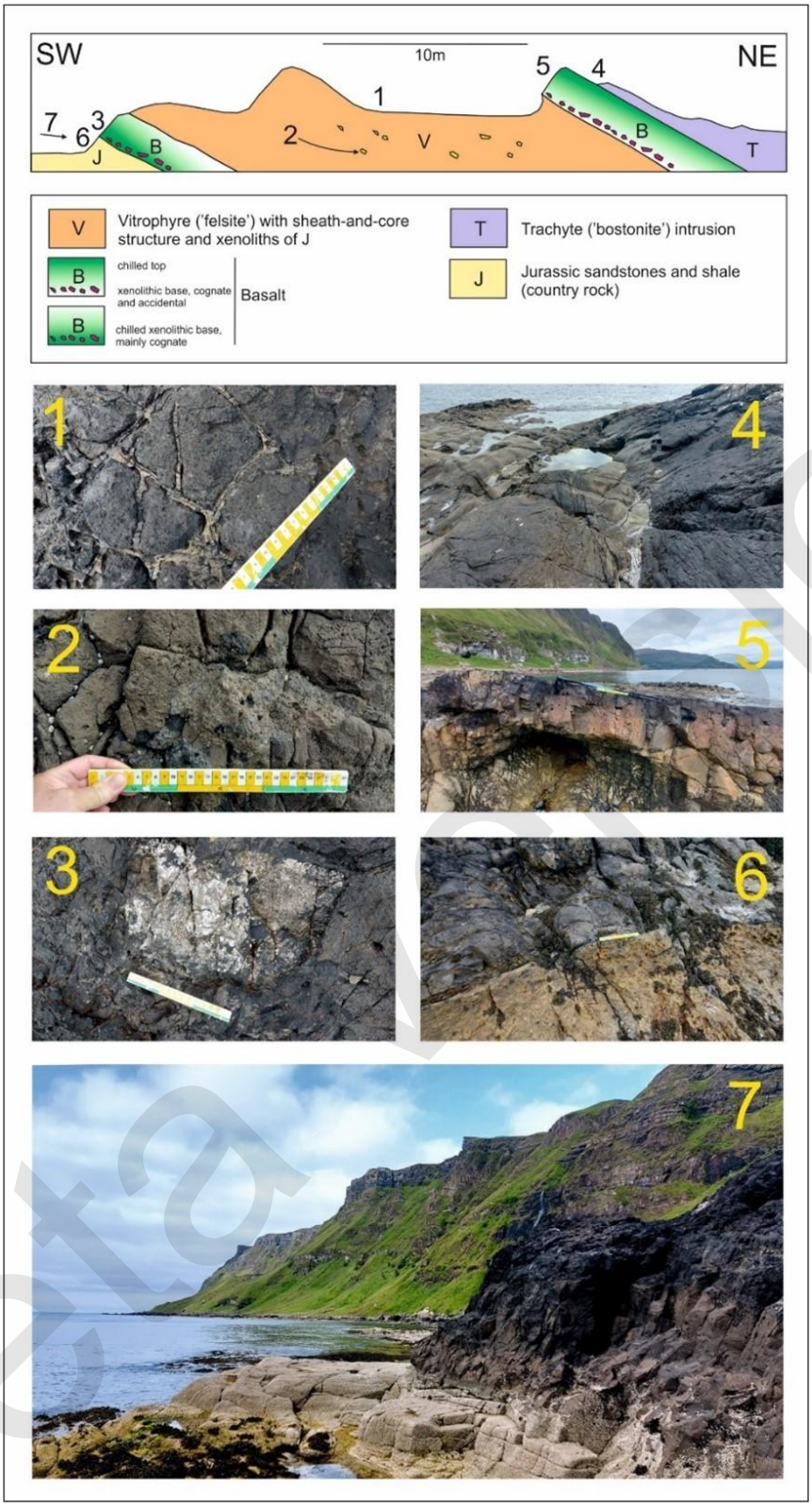


Figure 8-85: Schematic cross-section of the xenolithic, composite Rubha a' Chromain Sill, south coast of Brolass, SW Mull, with numbered field views: 1, sheath-and-core structure in central vitrophyre ('felsite'); 2, xenolith in central vitrophyre ('felsite'); 3, xenolith in lower basalt; 4, upper contact with trachyte ('bostonite'); 5, upper basalt; 6, lower basalt – Jurassic country-rock strata contact; 7, general view of lower part of sill, intruded into Jurassic sedimentary rocks (after Bailey *et al.* 1924). [Photographs courtesy of James Westland]

Some of the upper crustal xenoliths, interpreted to have been derived from the Moine Supergroup basement (Chapter 2), have undergone melting, ultimately forming glassy masses, referred to as buchites, due to rapid cooling. Within the buchites are a variety of aluminous minerals, including

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sapphire, spinel, cordierite and anorthite. Less commonly, for example in the Rubha a' Chromain Sill, west of Carsaig Bay on the south coast of Brolass, are sandstone and conglomerate xenoliths derived from the local Mesozoic country-rocks (Figure 8-85).

The sills are described in detail by Bailey *et al.* (1924). These early studies were concerned mainly with the complex high-temperature mineral assemblages due to pyrometamorphism that developed within crustal xenoliths prior to and/or during sill emplacement. More recently, Brearley (1986) described the melting reactions of the Moine basement materials, and Kille *et al.* (1986) inferred that the sill magmas were actively convecting during emplacement, maintaining high temperatures at the contacts, which resulted in localised thermal erosion of the pelitic Moine wall-rocks. Three of the most informative sills crops out at Tràigh Bhàn na Sgùrra, on the south coast of Brolass (Figure 8-86; Figure 8-87; Figure 8-88; Figure 8-89; Figure 8-90; Figure 8-91; Figure 8-92; Figure 8-93; Figure 8-94; Figure 8-95), Killunaig, on the south side of Loch Scridain (Figure 8-96; Figure 8-97; Figure 8-98; Figure 8-99**)**, and Kilfinichen, on the north coast of Loch Scridain (Figure 8-100).



Figure 8-86: Xenolithic, prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull.

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Figure 8-87: Xenolithic, prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull.



Figure 8-88: Xenolithic, prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull. The grey rock with the vertical fabric is country-rock Moine Supergroup strata. Sheep for scale.

Review version



Figure 8-89: Xenolithic, prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull. The grey rock with the vertical fabric is country-rock Moine Supergroup strata. Sheep for scale.

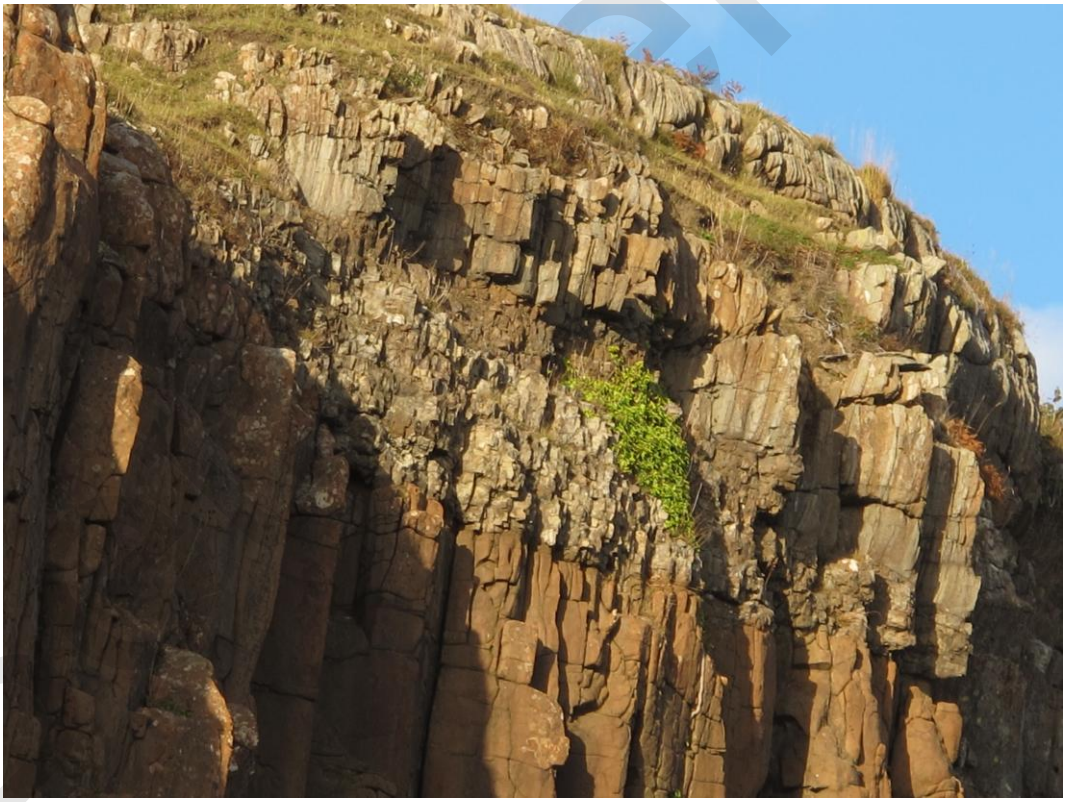


Figure 8-90: Detail of xenolithic top of prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull.



Figure 8-91: Detail of xenolithic top of prismatic-jointed sill, east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull.



Figure 8-92: Xenolithic, columnar-jointed sill (orange) forming the promontory on east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull. The rock with the vertical fabric is country-rock Moine Supergroup strata. People for scale.

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Figure 8-93: Thermally altered Moine Supergroup psammites, with vertical fabric, above upper margin of sill, on promontory on east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull. Pole *ca.* 1 m long.

Transgressive sill-country-rock contacts (Figure 8-94; Figure 8-95) suggest that heat transfer from the magma into the wall-rocks as it rose through the sill-complex conduits towards (or to) the contemporaneous land surface was aided by the turbulent nature of its flow (Kille *et al.* 1986).

The *ca.* 6 m thick Traigh Bhàn na Sgùrra sill has sharp contacts with Moine Supergroup country-rocks and systematic vertical textural variations (Holness & Humphreys 2003). In the lower *ca.* 10 m, plagioclase and clinopyroxene crystal size decreases upwards, recording deposition of settled crystals; above, crystal size increases upwards through *ca.* 3 m, while a complementary coarsening-downward trend occurs near the roof, giving a symmetrical profile. Holness & Humphreys (2003) quantified plagioclase aspect ratios and clinopyroxene–plagioclase–plagioclase dihedral angles (Θcpp), both sensitive to cooling rates. Θcpp is low at chilled margins, rises to higher values in the sill interior, then falls again near the roof, mirroring crystal-size trends. These data show that the sill crystallised under conditions of convection, crystal settling, compaction, and melt migration rather than static cooling. Importantly, it is demonstrated that such microstructural metrics can be used to reconstruct original sill thickness and emplacement dynamics, making the Traigh Bhàn na Sgùrra sill a benchmark for quantifying solidification processes in mafic intrusions.

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Figure 8-94: Transgressive contact between (stratified) Moine Supergroup psammites and (orange) dolerite sill, promontory on east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull, formed by localised melting by magma flow. Pole *ca*. 1 m long.



Figure 8-95: Detail of transgressive contact between (stratified) Moine Supergroup psammites and (orange) dolerite sill, promontory on east side of Tràigh Bhàn na Sgùrra, south coast of Brolass, SW Mull, formed by localised melting by magma flow. Pole *ca*. 1 m long.

The Killunaig and Kilfinnichen sills contain a wide spectrum of accidental xenolith types, most obviously: mullite buchites; cordierite buchites; and, siliceous psammite from the Moine Supergroup (Figure 8-96; Figure 8-97).

Borehole version



Figure 8-96: Xenolithic sill, Killunaig, north coast of Brolass, SW Mull. Pole *ca*. 1 m long.



Figure 8-97: Angular xenolith of siliceous psammite from the Moine Supergroup in the Killunaig Sill, north coast of Brolass, SW Mull. Pole *ca*. 1 m long.

The aluminous xenoliths are dominated by glass produced by melting of the xenolith, hence the term buchite is used. Most important are: mullite buchites, with a mass of mullite needles ($3Al_20_3.2Si0_2$) set in clear glass, pale lilac in hand-specimen (Figure 8-98; Figure 8-99; Figure 8-100); and, cordierite buchites, with crystals of cordierite ($(Mg,Fe)_2Al_3(Si_5AlO_{18})$ in a dark brown glass (Figure 8-101). Reaction rims around the margins of these buchites are typically rich in coarse-grained anorthite ($An_{87–60}$) formed by high temperature interaction - possibly involving diffusion - between basaltic (sill) magma and the aluminium-rich buchite, whilst both were essentially liquid (Figure 8-102; Figure 8-103). Pockets of quenched, isotopically contaminated basic glass with skeletal plagioclase and clinopyroxene occur 'trapped' between the plagioclase crystals. Sapphire crystals, not of gem quality, are relatively common (Figure 8-104).



Figure 8-98: Elongate mullite buchite (xenolith) within the Killunaig Sill, north coast of Brolass, SW Mull. Lens cap ca. 8 cm across.

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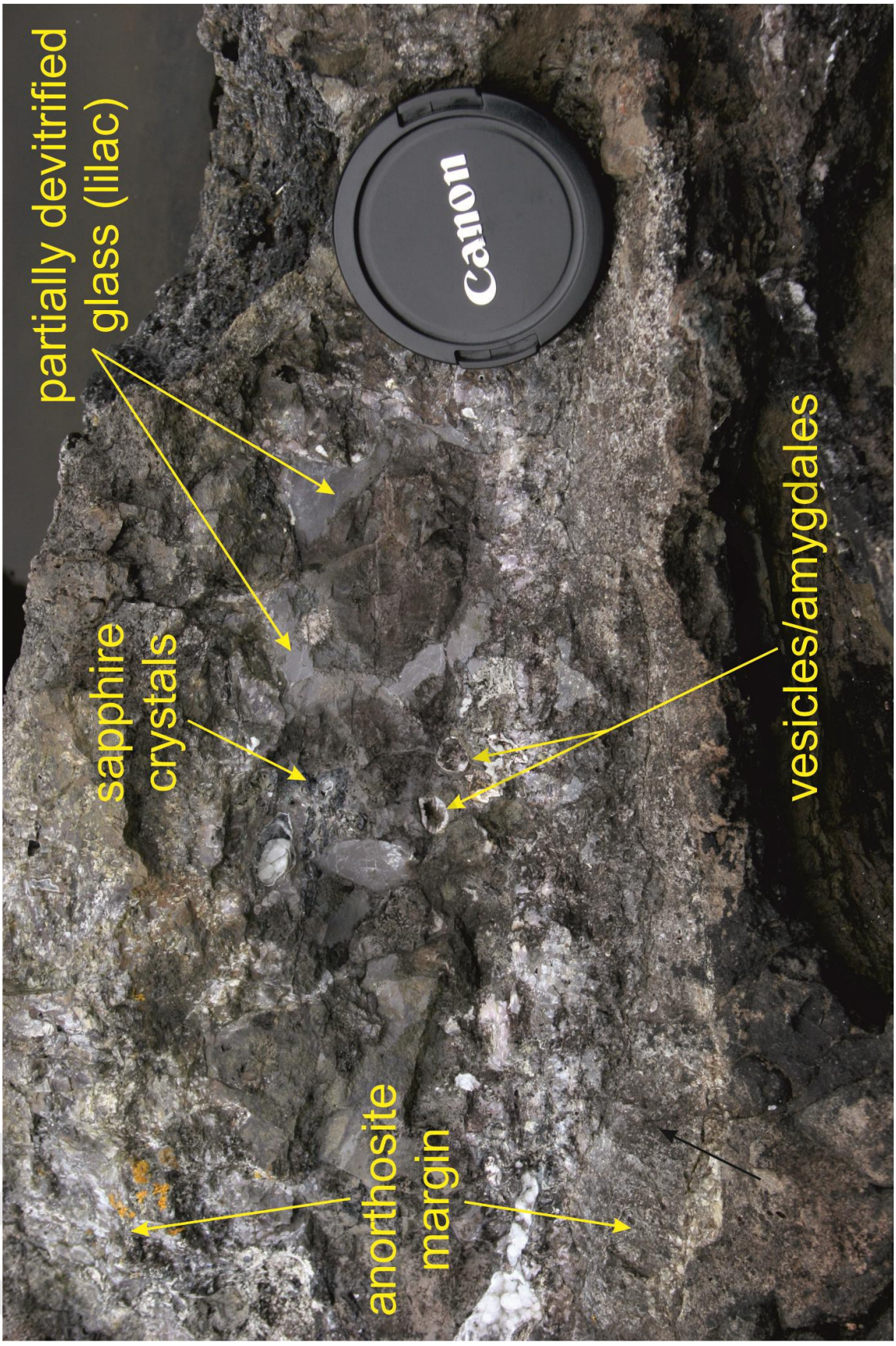


Figure 8-99: Detail of mullite buchite (xenolith) within the Killunaig Sill, north coast of Brolass, SW Mull. Lens cap *ca*. 8 cm across.



Figure 8-100: Detail of mullite buchite (xenolith) with dark blue, fractured sapphires within the Kilfinichen Sill, north coast of Loch Scridain, SW Mull. Coin *ca.* 24 mm across. [Photograph courtesy of John Faithfull]



Figure 8-101: Black, glassy cordierite buchite, Killunaig Sill, north coast of Brolass, SW Mull. Compass *ca.* 10 cm long.



Figure 8-102: Plagioclase (anorthosite) rimmed mullite buchite, Killunaig Sill, north coast of Brolass, SW Mull. Compass *ca.* 10 cm long.



Figure 8-103: Elongate mullite buchites with anorthosite-rich reaction rims within the Kilfinichen Sill, north side of Loch Scridain, SW Mull. [Photograph courtesy of John Faithfull]



Figure 8-104: A mineral separate of sapphires from the Rubha a' Chromain Sill, south coast of Brolass [Photograph courtesy of John Faithfull]

The highly aluminous composition of the buchite glasses and the associated minerals are consistent with their derivation from a clay-rich (i.e. aluminium rich) sediment or its metamorphic equivalent, most likely the pelites of the Moine Supergroup, by a multi-stage process (Dempster *et al.* 1999).

Hence, the intrusion of the Loch Scridain sills affected the country-rocks at different stages of their interaction:

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Process	Effect on Rock
Magma intrusion	Heats wall rock
Contact metamorphism	Forms buchite
Mineral reaction/diffusion	Forms reaction rim; plagioclase, mullite, sapphire etc.
Melt–rock interaction	Alters both sill and xenolith chemistry
Partial melting of xenoliths	Produces hybrid zones

Holness (2002) demonstrated, through microstructural analysis, that plagioclase crystal shapes and distributions in the sills reveal whether the magma was convecting or stagnant during cooling, and estimated that turbulent magma flow lasted *ca*. 5 months, forming a *ca*. 3 m metamorphic aureole. This reflects high emplacement temperatures, leading to: partial melting of pelitic country-rock, multiple generations of microcracking, melting at quartz-feldspar crystal boundaries, and breakdown of minerals such as muscovite and biotite. Despite pervasive cracking, melt segregation was limited over the observed timescales.

Some of the more evolved sills - andesitic and rhyolitic - are glassy, i.e. vitrophyres (the 'pitchstones' of older literature; Bailey *et al*. 1924) and have so-called sheath-and-core structure, in which tight, curving folds with hinge-line curvature exceeding 90° (typical of sheath folds) occur close to the margins of the sills (Figure 8-105; Figure 8-106) (Bailey *et al*. 1924; Drysdale 1979).

Core-rim differentiation, involving alternating silicic ('pitchstone') cores and less evolved rims, is another feature of these sills. The sheath-fold and core-rim structures reflect high strain and dynamic flow during emplacement, indicating that the magma was highly viscous and capable of complex deformation under directed stress (Drysdale 1979), thus providing an insight into the rheological and tectonic dynamics operating during emplacement.

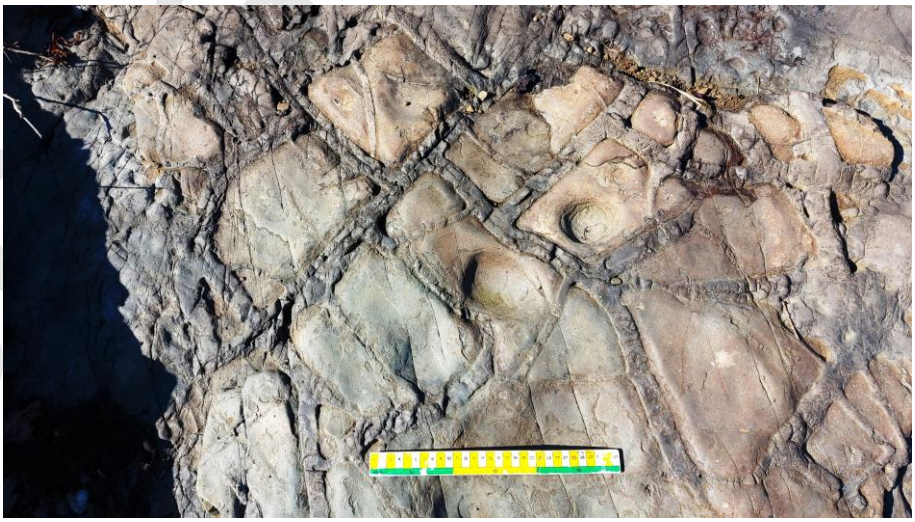


Figure 8-105: The glassy margin (vitrophyre or 'pitchstone') of the (non-porphyritic) andesitic Killiemore Sill, with sheath-and-core structure, on the north side of the eastern end of Loch Scridain. Scale *ca*. 30 cm. [Photograph courtesy of James Westland]

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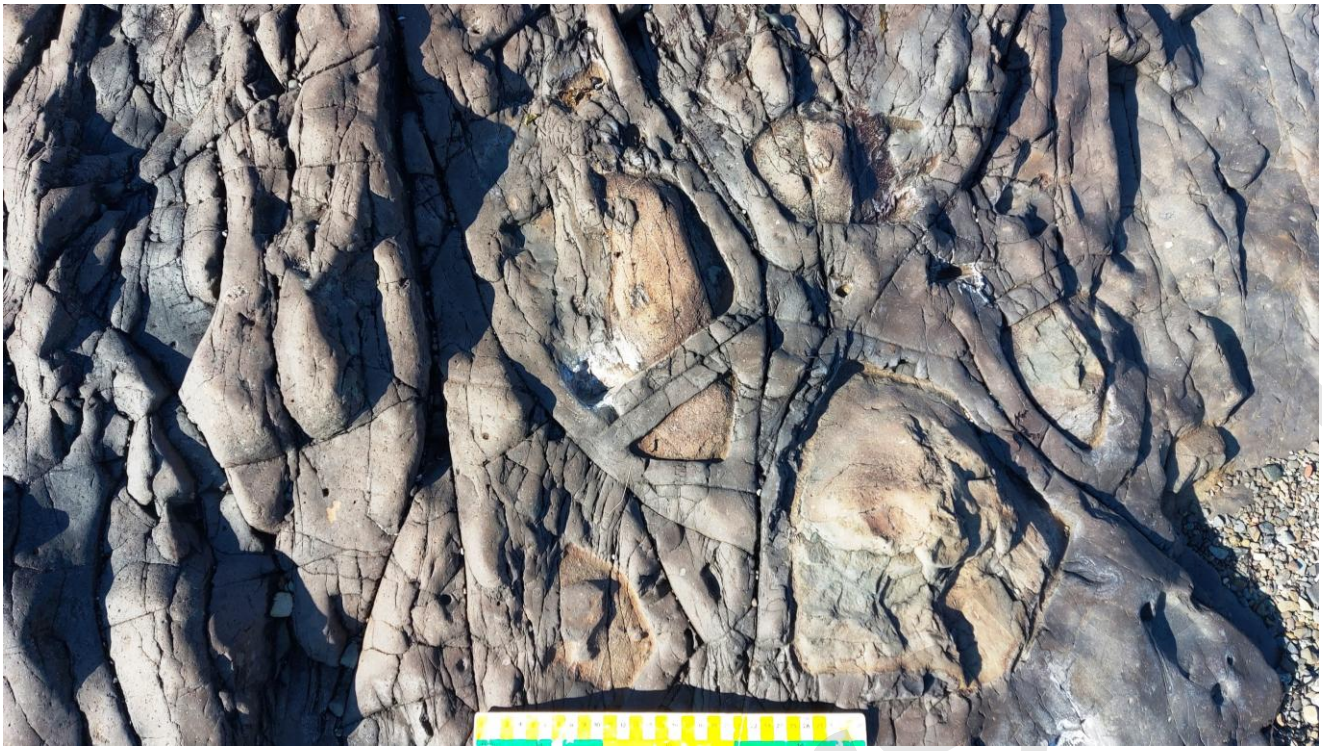


Figure 8-106: Detail of the sheath-and-core structure in the Killiemore Sill. Scale *ca*. 30 cm. [Photograph courtesy of James Westland]

8.4 Holy Isle and Dippin sills, Arran

Holy Isle, on the east side of Arran, is dominated by a sheet of sanidine-microporphyritic trachyte *ca*. 250 m thick, emplaced into Permian sandstones (Chapter 2) (Figure 8-107). This peralkaline intrusion is riebeckite-bearing, similar to the microgranite intrusion that forms Ailsa Craig (Chapter 9). Other related intrusions are sills or transgressive sheets of analcime-bearing olivine-dolerite which crop out around Lamlash Bay (Figure 8-108). These inclined sheets may have a focal point at depth in the vicinity of Lamlash Bay, akin to the focal point of cone-sheets associated with the Skye and Mull central complexes (Chapter 9).



Figure 8-107: Holy Isle, viewed towards the south from Clauchlands Point, east Arran. The high ground is composed of a sanidine-microporphyritic trachyte sheet, with the lower ground consisting of country-rock Permian sandstones.

Beta version



Figure 8-108: Transgressive sheet of prismatic-jointed, analcime-bearing olivine-dolerite, north of Clauchlands Point, north side of Lamlash Bay, east Arran.

The Dippin Sill is *ca*. 40 m thick at Dippin Head and forms a transgressive sheet emplaced into Triassic mudstones and siltstones (Chapter 3) (Figure 8-109) (Gibb & Henderson 1978). It is a composite intrusion, with a thick central unit of analcime-bearing olivine-dolerite ('crinanite') bounded top and bottom by analcime dolerite ('teschenite'). Pegmatitic facies occur sporadically throughout the sill. The parental magma was of alkali olivine basalt type that fractionated within a magma chamber at a deeper level than the sill. The first phase of intrusion involved relatively evolved magmas from the upper part of the chamber, followed by intrusion into the central part of the sill of less evolved magmas carrying suspended olivine, with or without plagioclase crystals from the lower part of the chamber. As with the Little Minch Sill-complex (see above), flow differentiation of the magmas occurred during emplacement, together with assimilation of material from the conduit walls. The numerous pegmatitic segregations are the product of late-stage filter pressing within the crystallising body. Several subsolidus processes are also recognised, including decomposition of magmatic nepheline (± alkali feldspar) to produce analcime; circulation of hydrothermal (meteoric) fluids caused the formation of secondary serpentine, chlorite, iron oxides, and natrolite and other zeolites.

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Figure 8-109: The Dippin Sill, SW of Dippin Head, SE Arran, comprising a thick central unit (exposed) of analcime-bearing olivine-dolerite ('crinanite'), bounded top and bottom by analcime-dolerite ('teschenite').



Figure 8-110: The prismatic-jointed central unit of the Dippin Sill, an analcime-bearing olivine-dolerite ('crinanite'), SW of Dippin Head, SE Arran.

8.5 Micrographitic and rhyolitic sills, south Arran

These thick silicic sills form prominent crags at Brown Head, south of Drumadoon Bay, and inland for some distance to the east (Figure 8-111) (Tyrrell 1928). They are most likely linked to dykes of similar composition, for example those that crop out south of Corrygills Point on the east coast. In some respects, these sills are gradational with certain composite sills (Section 8.6).



Figure 8-111: Microgranite sill forming inland crags at Brown Head, SW Arran.

Most of the sills are conspicuously porphyritic, with phenocrysts of quartz and alkali feldspar, up to 1 cm and 1.5 cm long, respectively, set in a fine-grained groundmass. Sparse phenocrysts of sodic plagioclase are also present. Commonly, the phenocrysts are anhedral, suggestive of some form of magmatic corrosion by the groundmass 'liquid'.

8.6 Composite sills of Arran and south Bute

These composite sills are up to 80 m thick and form some of the higher ground in south Arran, including the prominent cliffs at Bennan Head and at Drumadoon (Figure 8-112; Figure 8-113) on the west coast. Typically, they comprise a volumetrically dominant, central silicic unit ('felsite') (Figure 8-114) flanked by relatively thin basaltic or (quartz) doleritic units, although some consist of the reverse: a central doleritic unit, flanked by marginal felsites (Rogers & Gibson 1977; Macgregor 1983). The prismatic-jointed sill which forms the bulk of Pladda, off the south coast of Arran, is attributed to this group and is composed of quartz dolerite (Figure 8-115). The Arran composite sills and dykes generally postdate the emplacement of the Holy Island and Dippin alkaline sills.



Figure 8-112: Prismatic-jointed composite sill forming The Doon, north of Drumadoon Point, west Arran, a microgranite ('felsite'), flanked (top and bottom) by (poorly exposed or absent) marginal doleritic units. Height of summit (cliff) 59 m OD.

Beta version



Figure 8-113: Prismatic-jointed composite sill forming The Doon, north of Drumadoon Point, west Arran, a microgranite ('felsite'), flanked (top and bottom) by (poorly exposed or absent) marginal doleritic units.



Figure 8-114: Central quartz-alkali feldspar porphyritic felsite of the Drumadoon Sill, west Arran. Coin *ca.* 24 mm across.



Figure 8-115: Prismatic-jointed quartz dolerite sill intruded into Triassic strata on Pladda, off the south coast of Arran, belonging to the suite of composite sills.

The internal contacts between the basic and the silicic units are typically gradational over a few tens of centimetres and 'xenoliths' or pillow-like masses of basic material may occur within the silicic unit (Figure 8-116). Within the xenoliths are xenocrysts of feldspar and/or quartz of the type seen in the silicic unit. Locally, marginal felsites vein the central dolerite (Figure 8-117). These intimate compositional relationships are suggestive of mixing processes, initially prior to intrusion, explaining the xenocrysts in the basic units, and then during intrusion, explaining the gradational contacts and the xenoliths of basic material in the silicic material (Rogers & Gibson 1977).



Figure 8-116: Pillow-like masses of basic material within the silicic unit of the Drumadoon Sill, west Arran. Coin *ca.* 24 mm across.

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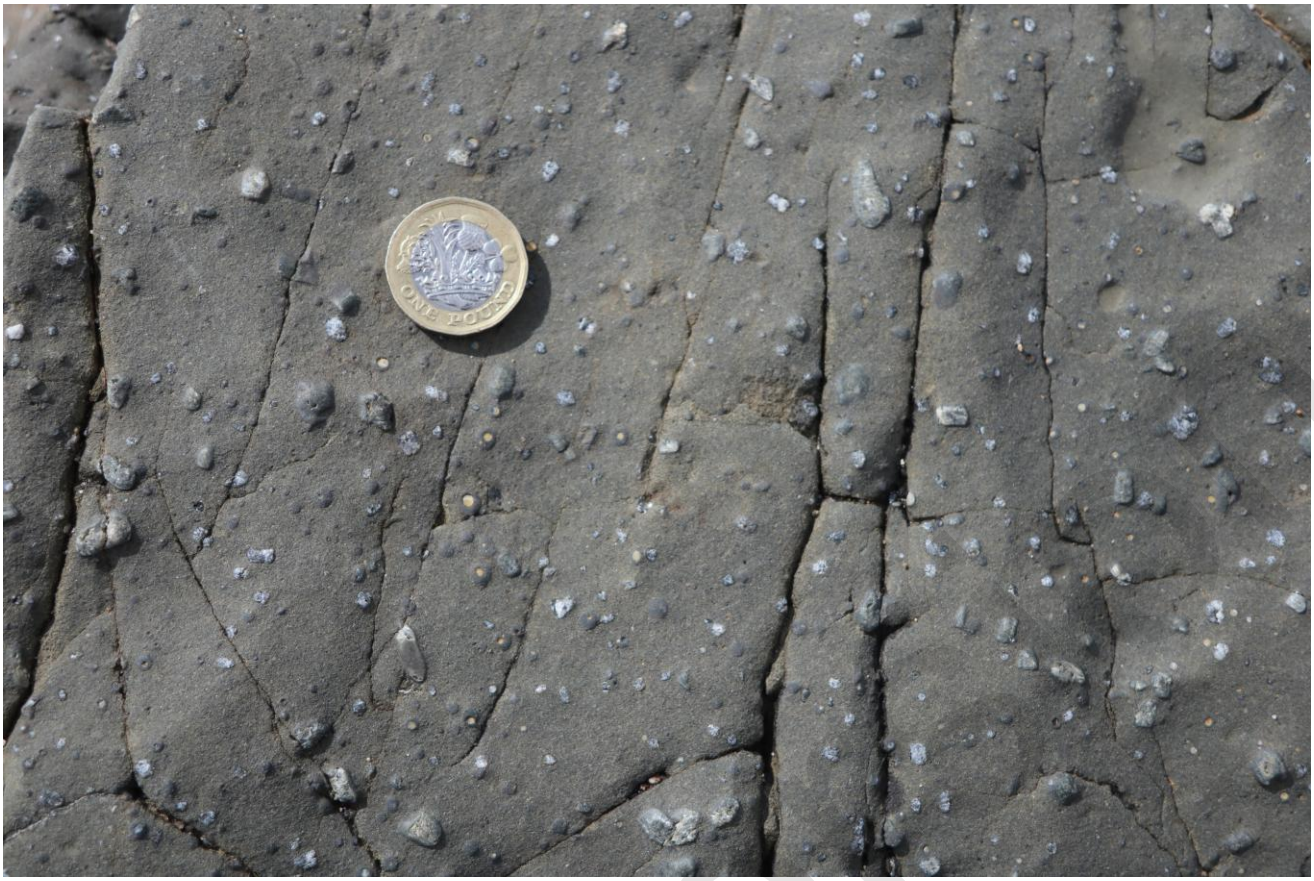


Figure 8-117: Basaltic unit with inclusions of microgranite in the Drumadoon Sill, west Arran. Coin *ca.* 24 mm across.

8.7 Tighvein Intrusion-complex, Arran

Augite diorite in gradational contact with underlying xenolithic quartz-dolerite is intruded conformably into Triassic strata at Tighvein, in south Arran. Intrusions of microgranite, some granophyric, cut the augite diorite, which is also extensively veined by microgranite. The quartz-dolerite and augite diorite form a sill, but the microgranitic intrusions are steep-sided and may be parts of a ring-dyke (Herriot 1975). Other sheets and dykes of felsite and porphyritic rhyolite cut the whole 'complex', together with dykes of vitrophyre ('pitchstone') and tholeiitic basalt. The xenoliths in the quartz-dolerite are a fine-grained basic rock in various stages of digestion.

Beta version

8.8 Raasay granite sill

The Raasay granite Sill crops out over a significant part of the southern half of Raasay (Figure 8-118) and is the only unequivocal significant concordant granitic intrusion in the Skye-Raasay area.

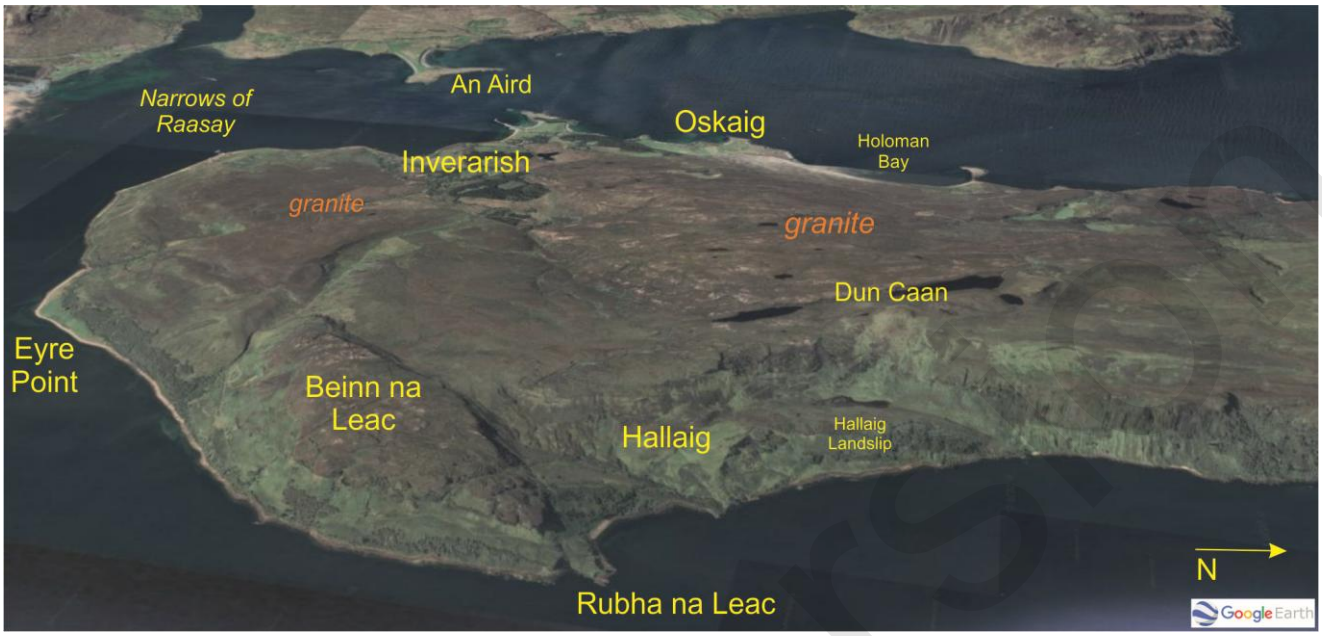


Figure 8-118: Oblique Google Earth© image illustrating the nature of the outcrop of the Rassay granite sill. View towards the west.

It is referred to as a granophyre sill based on the common development of its two key minerals, quartz and alkali feldspar, in a distinctive texture referred to as a granophyric intergrowth, or texture. Quartz and alkali feldspar are also present as phenocrysts, typically up to 5 mm, and the main ferromagnesian mineral is the alkali-rich amphibole, riebeckite, blue when fresh, but typically weathered to a rusty brown on most surfaces. Close to non-faulted contacts, the granite tends to be relatively fine-grained, essentially a very pale microgranite or felsite. Some of the uncommon apophyses of the granite have a spherultic texture, indicating rapid cooling of the granitic magma. Near Loch Storab, relatively close to the centre of the northern outcrop (see below), auto-intrusive veins of the microgranite/felsite, up to *ca.* 30 cm across, contain needles of riebeckite. In the same area, the granite is a host to veins containing cavities (druses) with faceted crystals of quartz, alkali feldspar and riebeckite (Figure 8-119) (Davidson 1935), implying relatively low-pressure crystallisation at a shallow depth below the contemporaneous land surface.

Beta version



Figure 8-119: Cavities (druses) with faceted crystals of quartz, alkali feldspar and riebeckite within the Rassay granite sill. Main cavity *ca.* 10 mm across.

There are two main outcrops, together with several small, isolated masses (due to present-day erosion). The smaller southernmost outcrop is in the area between Inverarish and Suisnish and has the more complex contacts, in place relatively concordant with its country-rocks, predominantly Triassic and Lower Jurassic Ardnish Formation and Pabay Shale Formation strata (Figure 8-120; Figure 8-121; Figure 8-122), whereas its contacts with Torridonian strata are interpreted as faults (BGS 2006a).



Figure 8-120: Field view of the Rassay granite sill from Maol na Gainmhich on Skye. The pale sill forms the obvious crags above the coast and is underlain by dark Lower Jurassic Pabay Shale Formation strata. View towards the north. The Storr, Trotternish, in the distance.

Beta version



Figure 8-121: The concordant, near-horizontal, fine-grained, lower contact of the southern outcrop of the pale-weathering Raasay granite sill, intruded into dark, Lower Jurassic Pabay Shale Formation strata (now hornfelsed), on the landward side of the road at Suisnish Point. Pole *ca*. 1 m long.



Figure 8-122: Minor transgression of the Raasay granite sill, within Lower Jurassic Pabay Shale Formation shales, on the landward side of the road at Suisnish Point.

Beta version

The northern outcrop is intruded at a higher stratigraphic level, between the Middle Jurassic Bearreraig Sandstone Formation and the Great Estuarine Group. Along its eastern margin, this outcrop of the granite has a faulted contact, predominantly against basaltic lavas, with an escarpment trending NNW-SSE and giving rise to the elongate Loch na Meilich (Figure 8-123) and Loch na Mna.



Figure 8-123: Escarpment of the Raasay granite sill (on left), in faulted contact with more easily eroded and poorly exposed Middle Jurassic Bearreraig Sandstone Formation strata (on right). The elongate Loch na Meilich is located on the Jurassic rocks. View from south of the path at Bealach Ruadh, towards the north.

The sill also occurs on the nearby small peninsula of An Àird on Skye (Figure 8-124; Figure 8-125), suggesting a link with the granites of the Western Red Hills Intrusive Centre (Chapter 9). One possible correlation is with the Maol na Gainmhich Granite which, like the Raasay granite sill, is distinctly alkaline in composition and contains riebeckite.

Beta version



Figure 8-124: The An Àird peninsula (left of centre), composed of prismatic-jointed granite, which may be related to the main granite sill on Raasay.



Figure 8-125: Prismatic-jointed granite sill, An Àird, Narrows of Raasay.

8.9 Gars-bheinn ultrabasic sill, Skye

The Gars-bheinn ultrabasic sill crops out in the southern part of the Cuillin, on the southern side of Gars-bheinn, at *ca*. 300 m OD and has been described in detail by Weedon (1960) and by Bevan & Hutchison (1984) (Figure 8-126). It extends for *ca*. 300 m from east-to-west and is composed of feldspathic

peridotite, with the upper 15 m of this 80 m thick intrusion comprising alternating layers or bands of plagioclase-rich pegmatoid material (Figure 8-127; Figure 8-128). The sill is intruded into Paleocene basaltic lavas and a possible feeder dyke to it cuts the underlying Late Proterozoic Torridonian strata (Chapter 2). The base of the sill is not exposed, although the lower portion appears to be connected to the inferred feeder dyke. Marginal chill facies are present but are not obvious in the field.

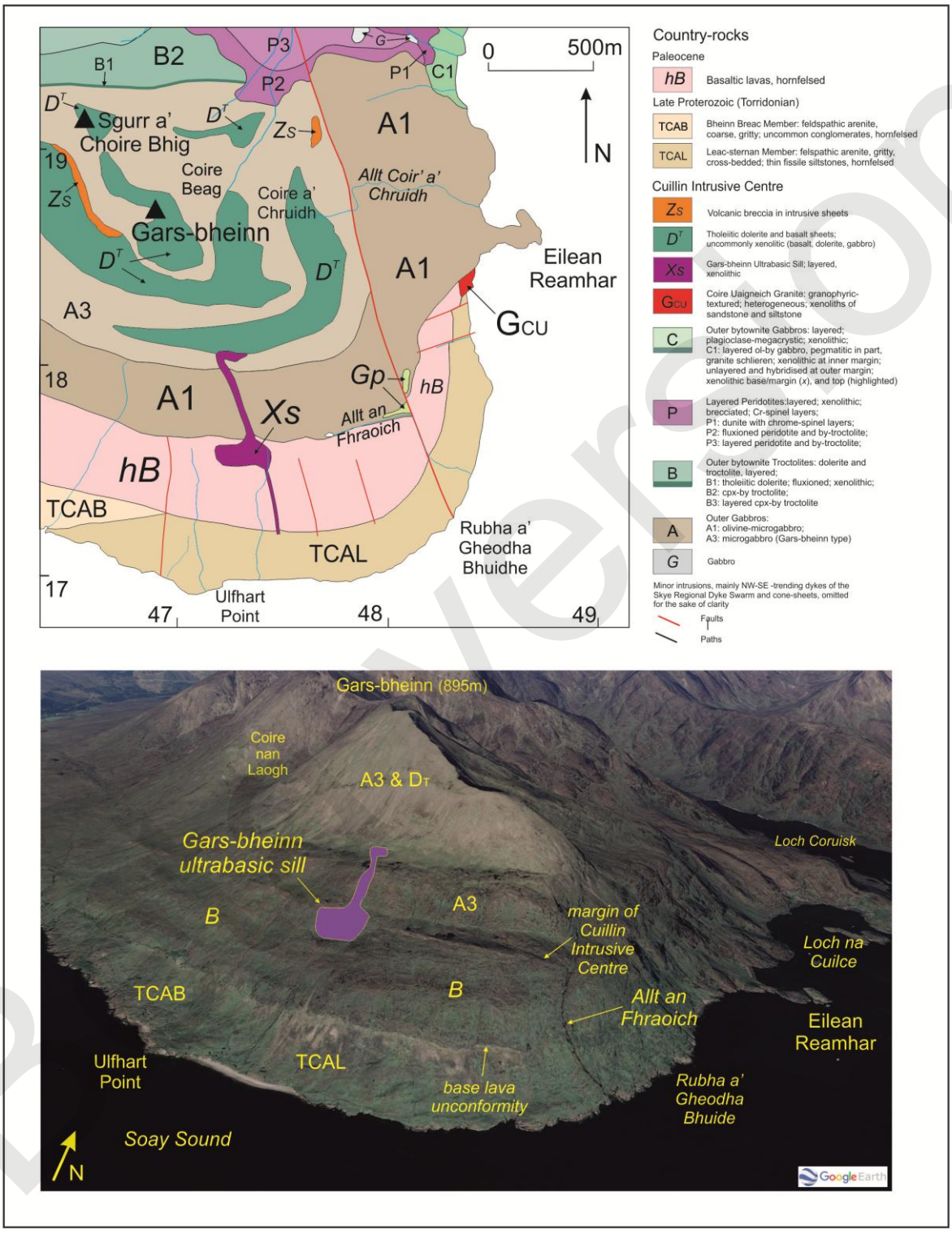


Figure 8-126: Oblique Google Earth© image and simplified geological map illustrating the location of the Gars-bheinn ultrabasic sill on the south side of the Cuillin, Skye.

Review version



Figure 8-127: General view of the stratified Gars-bheinn Sill, south of the Skye Cuillin, overlooking Soay Sound. Pole *ca.* 1 m long.

The plagioclase-rich layers in the upper part of the sill commonly have a pegmatoid texture, with individual crystals extending across the complete thickness of individual layers (10–20 cm). Clinopyroxene is interstitial to the plagioclase. Plagioclase crystals in these layers have compositions similar to those in the non-layered main (lower part) of the intrusion. Individual layers are thicker, up-sequence. The olivine-rich layers contain interstitial plagioclase and an Fe-rich clinopyroxene.

Compositional data from the chilled marginal facies of the dyke located below the sill indicate a parental picritic magma (Weedon 1960), with affinities to some of the ultrabasic dykes (Chapter 7) associated with the Cuillin Intrusive Centre (Chapter 9). Within the upper part of the sill, some olivine-rich layers have mineralogical and petrological features in common with these ultrabasic dykes.

According to Weedon (1960), the formation of the sill, including the well-developed layers in the upper part and the presence of pegmatoid structures in the plagioclase-rich portions, was dominated by crystal-liquid fractionation processes involving crystal settling. The main portion of the sill, consisting of unlayered feldspathic peridotite, was formed by gravitational settling of olivine crystals and intercumulus growth of plagioclase and clinopyroxene. Any liquid not involved in this intercumulus growth process was removed, by diffusion, compaction or convective mechanisms, thus enriching the magma above the crystal-liquid interface in Ca, Al, K, Na and volatiles, capable of crystallising the pegmatoid plagioclase-rich layers, referred to above. Further cumulus growth of olivine within unfractionated magma would give rise to the subsequent olivine-rich layer(s). This process was repeated several times. Increases in the thicknesses of individual plagioclase-rich layers, ‘up sequence’, may be attributed to an overall build-up of volatiles within the residual magma. The model of Weedon (1960), therefore, is temperature-independent and strongly controlled by local variations in magma composition.

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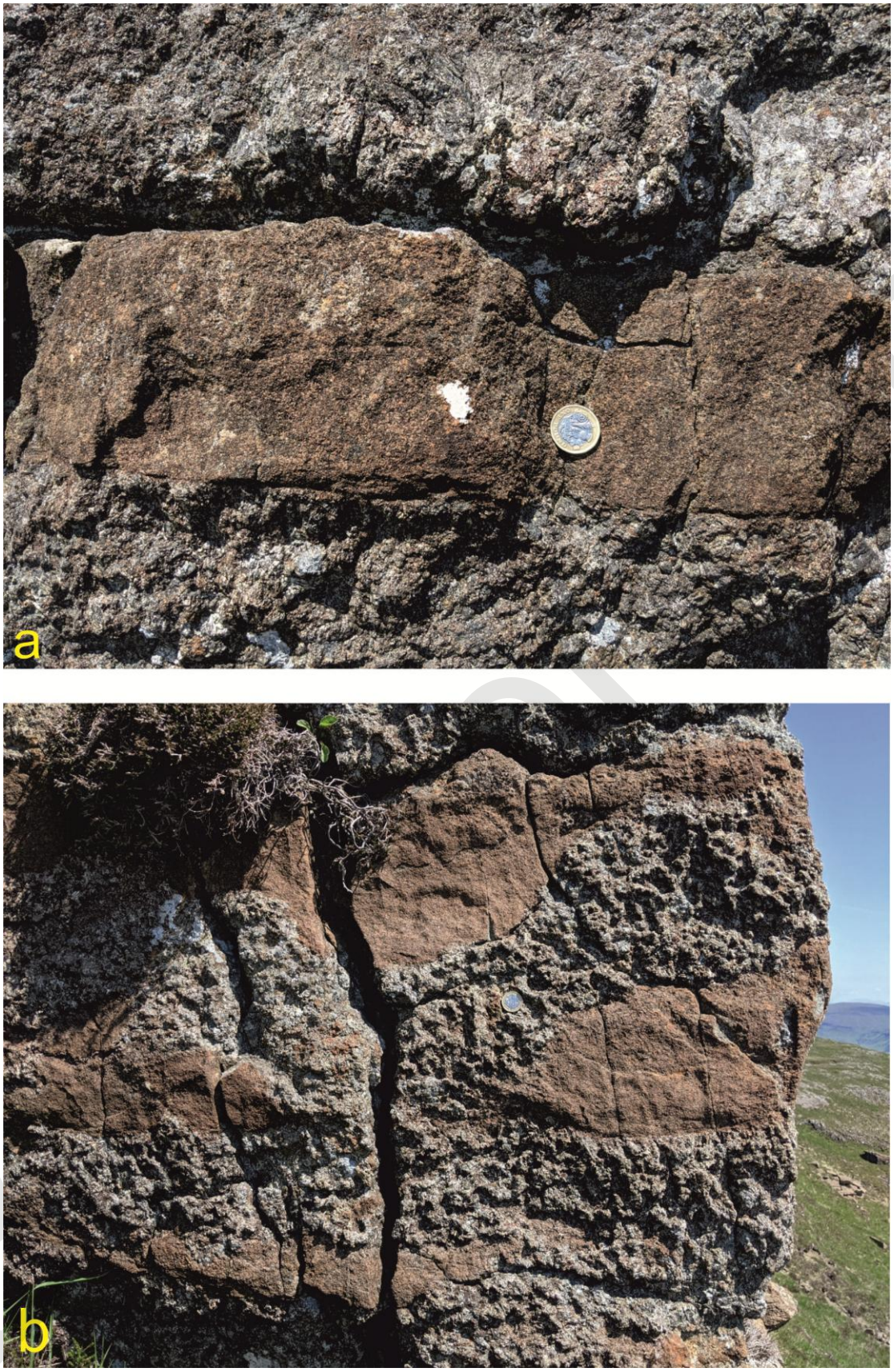


Figure 8-128: Field images of the upper part of the Gars-bheinn ultrabasic sill, with pale, transgressive plagioclase-rich pegmatoid layers within dark (orange) feldspathic peridotite ('host'). Coin *ca.* 24 mm across.

Based on a detailed re-investigation of the field relationships and mineralogy of the sill, Bevan & Hutchison (1984) describe cross-cutting and near-vertical attitudes to the pegmatioid material and concluded that these coarse-grained, plagioclase-rich layers were introduced in the form of high-temperature fluid 'sills' that were injected into already-crystallised peridotite. These sills appear to be related to the magma which crystallised to form the outer (bytownite-)gabbroic unit(s) of the Cuillin Intrusive Centre (Chapter 9) and are not co-genetic with the peridotite portions of the sill. Similar pegmatitic material occurs within nearby hornfelsed basaltic lavas.

8.10 Other sills

Other dolerite sills of probable Paleocene age occur at several localities within and on the periphery of the Hebridean Igneous Province. Thin dolerite sills intruded into Torridonian strata on Soay are good examples of classic fully concordant intrusions with prismatic/columnar joints (Figure 8-129)

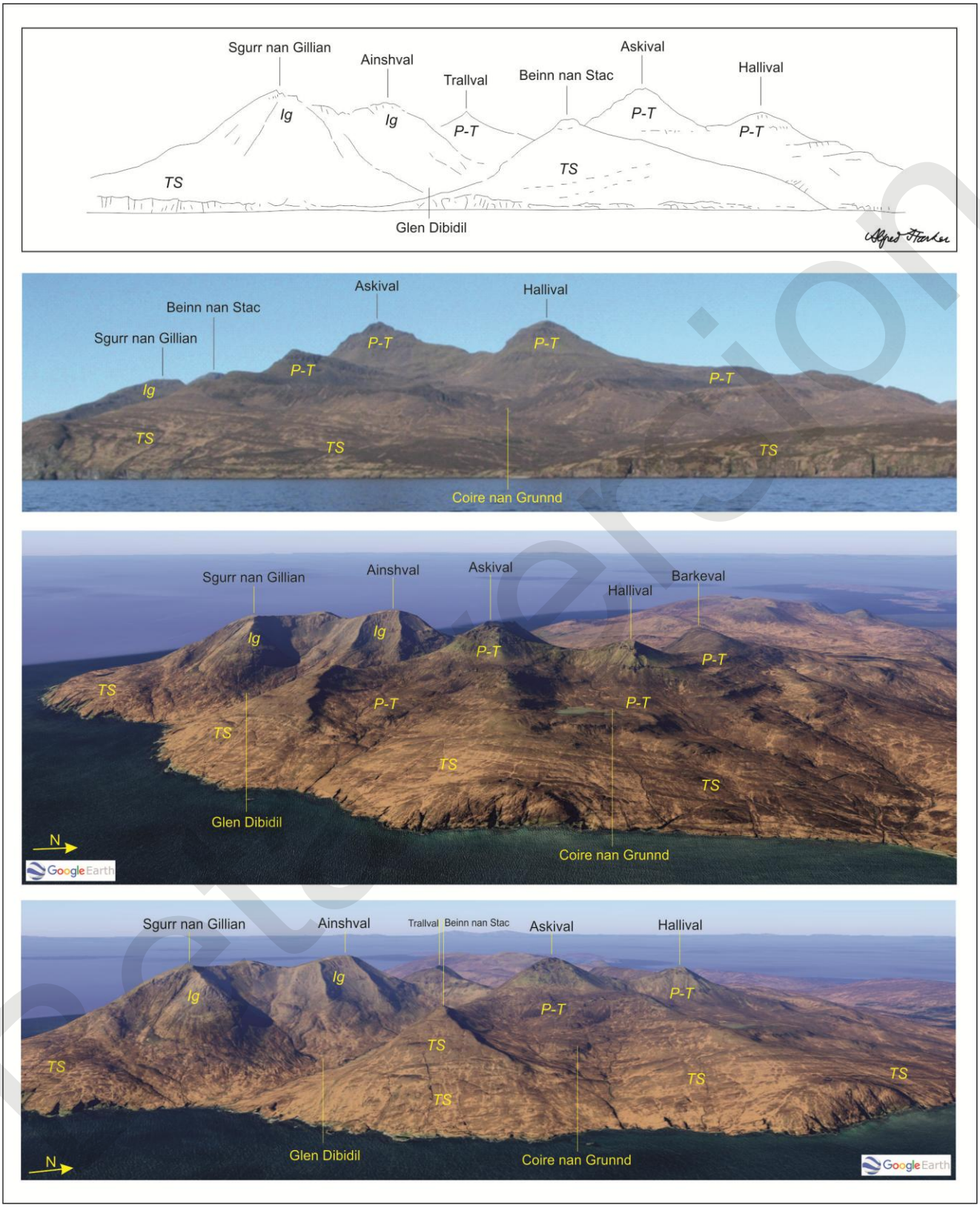


Figure 8-129: Thin dolerite sill with prismatic/columnar joints intruded into Torridonian strata, SE Soay.

Further afield, are a massive, easterly dipping sill, which intrudes gneisses at Lochmaddy, North Uist (Mackinnon 1974), and the Prestwick–Mauchline Sill-complex north of Ayr, which is petrographically similar to analcime-bearing olivine-dolerite sills on Arran and has yielded a K-Ar mineral age of 58 Ma (De Souza 1979).

Revision

9 Central complexes



The Rum Central Complex, with layered peridotites and troctolites (P-T) emplaced into country-rock Torridonian Supergroup strata (T) and ignimbrites (Ig) within the early Paleocene caldera

Publication

9.1 Introduction

The Hebridean Igneous Province (HIP) is one of the World's classic areas for the development of central complexes (Figure 9-1).

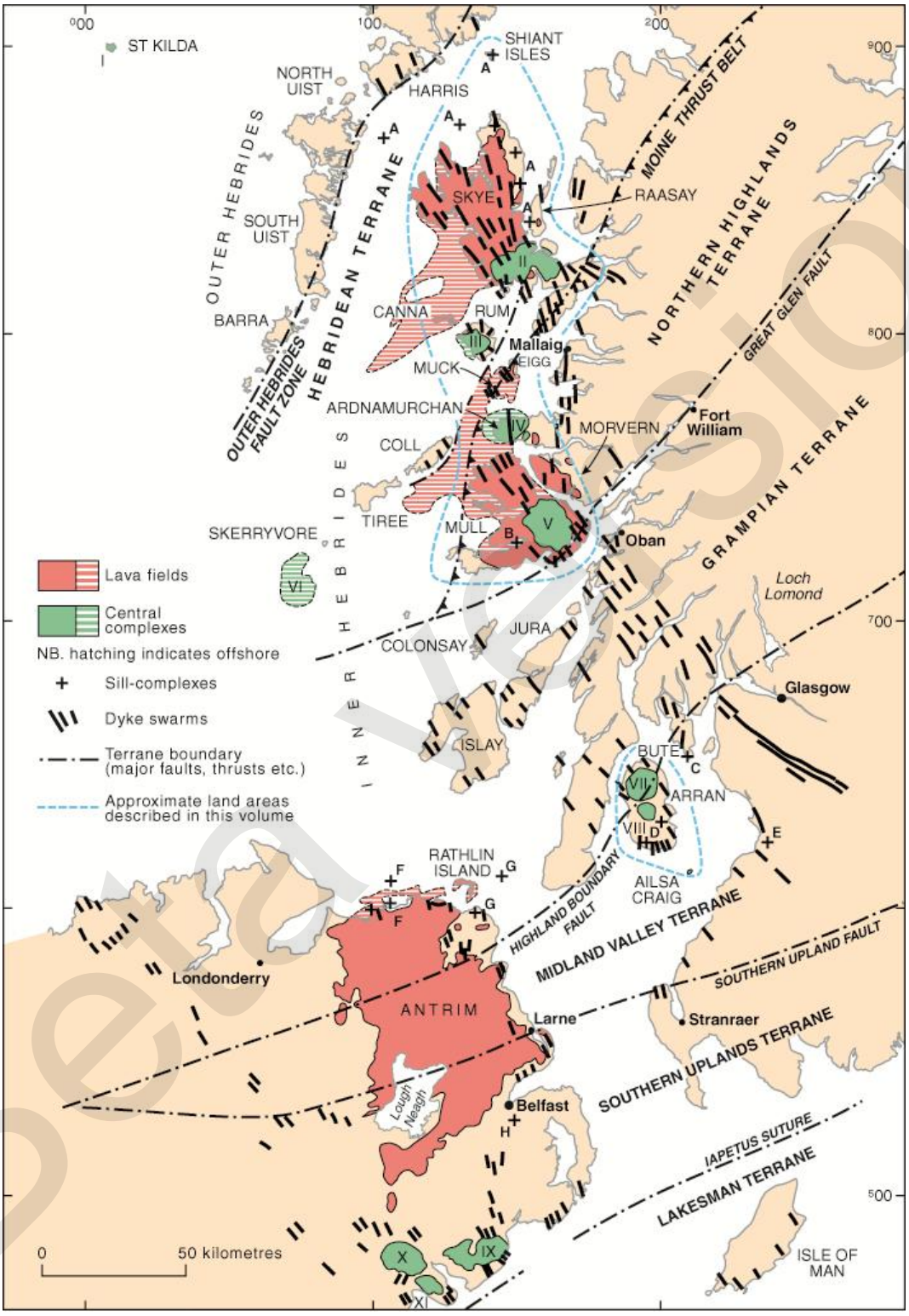


Figure 9-1: Simplified geological map showing the locations of Paleocene central complexes, lava fields, sill-complexes and dyke swarms in western Scotland and NE Ireland (after Emeleus & Bell 2005).

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Each central complex contains several igneous rock types in intimate relationships with various metamorphic and sedimentary country-rocks. The igneous rocks exhibit a variety of modes of intrusion and crop out within restricted, approximately circular areas, up to about 15 kilometres in diameter. These represent the eroded roots of central volcanoes and, where reliable age data are available, individual central complexes generally appear to have been relatively short-lived (Chapter 5). From initiation to decay, and subsequent unroofing, possibly took less than 1 m.y. in some instances. Most of the central complexes contain clear evidence of surface volcanism at an early stage in their evolution, and extrusive igneous rocks are commonly preserved within them. Conversely, the associated and relatively young, coarse-grained intrusions cooled and crystallised slowly at depth, most likely from 2 to 3 km. These coarse-grained intrusions were emplaced beneath an ever-growing volcanic superstructure (e.g. Skye, Rum, Mull), although some probably formed beneath a thick cover of country-rocks and may not have experienced associated surface volcanism (e.g. the North Arran Granite Pluton).

The central complexes were foci of intense, very localised magmatic activity dominated by basic (mafic) and/or ultrabasic (ultramafic) magmas derived from the Earth's upper mantle. These primitive magmas were usually accompanied by silicic magmas of mixed origin: (a) those generated through partial melting of the continental crust as this was traversed by the basic magmas; and, (b) those originating by fractionation of the basic magmas as they ponded in the upper crust (Chapter 10).

Most of the central complexes are sited on ridges of pre-Mesozoic rocks, at intersections of major N-S-trending lineaments with older cross-cutting (generally NE-SW) faults (Figure 9-2). The continental crust within the Hebridean Igneous Province is generally thinner than in adjoining areas (Meissner *et al.* 1986), which may have focussed the igneous activity (Thompson & Gibson 1991). The surrounding country-rocks comprise older Paleocene lava fields (Chapter 6), as for example on Skye and Mull, and/or basement lithologies, for example Lewisian gneisses and Torridonian sedimentary rocks on Rum, Dalradian metasedimentary rocks plus younger sedimentary strata on Arran, and Moine psammites and pelites on Ardnamurchan (Chapter 2). These basement lithologies are commonly overlain by attenuated basin-margin sequences of Triassic, Jurassic and Cretaceous strata (Chapter 3).

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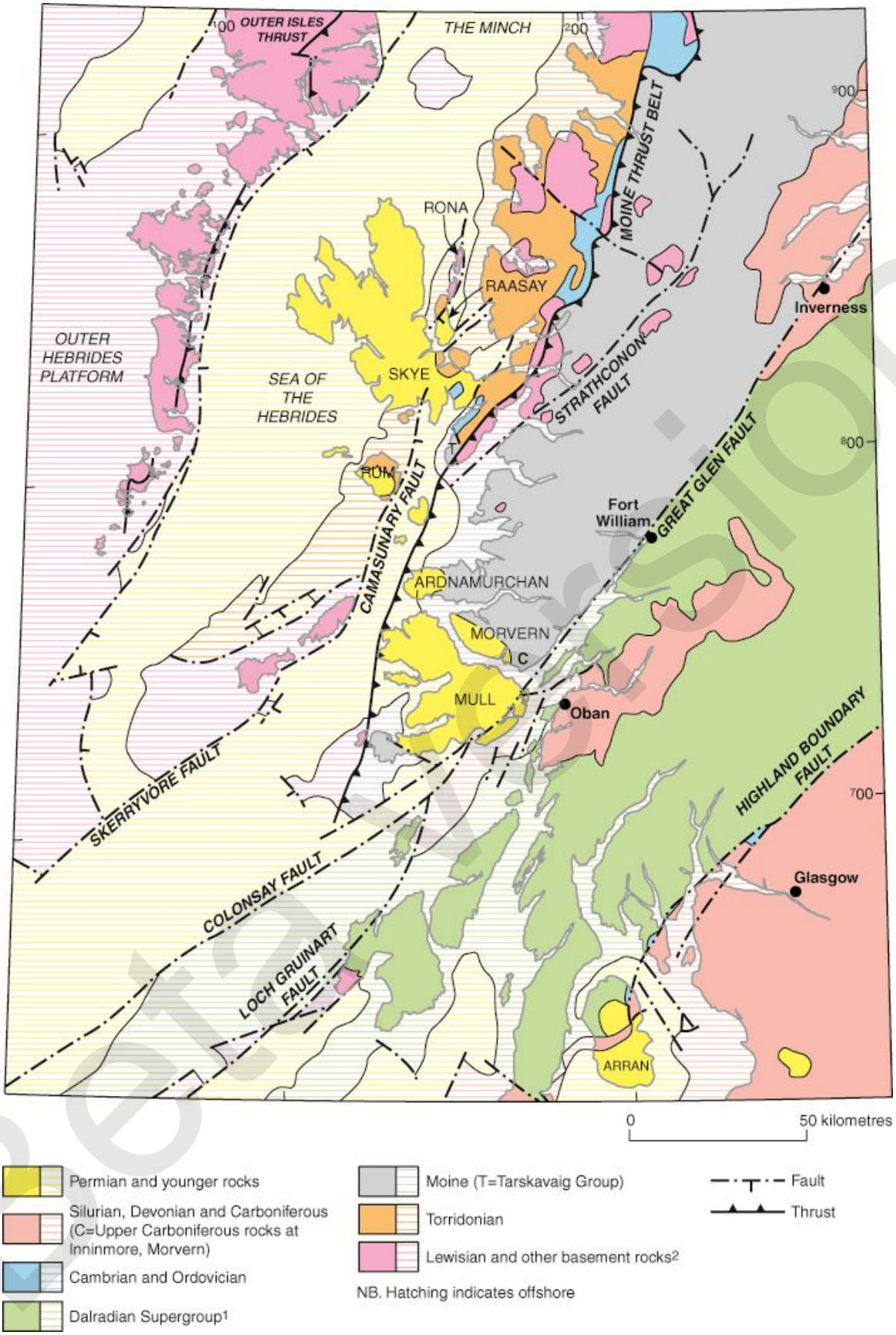


Figure 9-2: Onshore and offshore distribution of Precambrian and Lower Palaeozoic rocks along the western seaboard of Scotland (1, includes the Bowmore and Colonsay groups on and offshore Islay; 2, includes gneisses of the Rhinns Complex south of the Great Glen Fault) (after Emeleus & Bell 2005).

Beta Version

9.2 Form of the intrusions

The form or geometry of the intrusions depends on the lithologies involved, and four main associations are recognised.

9.2.1 Layered peridotites, troctolites and gabbros

Coarse-grained ultrabasic and basic rocks, such as peridotite, troctolite and gabbro, commonly form layered, relatively flat-lying sequences that may be several hundreds of metres thick and possibly dip at a shallow angle towards a focal point at a depth of a few kilometres, commonly with conspicuous topographic profiles (Figure 9-3; Figure 9-4; Figure 9-5; Figure 9-6; Figure 9-7; Figure 9-8; Figure 9-9; Figure 9-10; Figure 9-11; Figure 9-12; Figure 9-13). Alternatively, these basic magmas have formed sets of concentric conical intrusions (cone-sheets) with a focal point at depth (Section 9.2.2, see below). Ring-dyke intrusion models that were previously invoked to explain the arcuate plan view of certain large *basic* intrusions (e.g. Bailey *et al.* 1924; Richey 1932) are not now considered to be valid for several reasons. In particular, the central 'block' would have to drop to unrealistic depths along steeply inclined, outwardly dipping fractures to create the space necessary for intrusions that commonly have ring widths more than 1 km. The ring-dyke model of emplacement is considered valid for some of the silicic (granite, microgranite, rhyolite) intrusions, which are considerably thinner, commonly a few tens of metres (Section 9.2.4, see below).

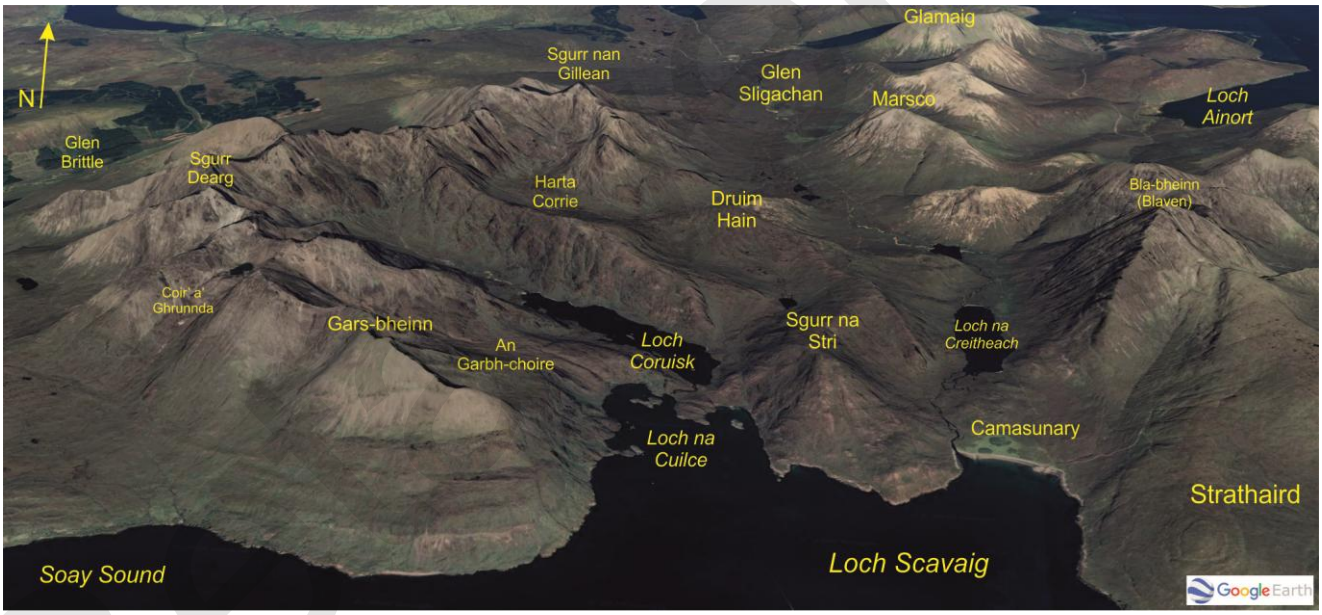


Figure 9-3: Oblique Google Earth© image of the glacially sculpted Cuillin, Skye, composed of peridotites, troctolites and gabbros, all intruded by dolerite cone-sheets, of the Cuillin Intrusive Centre, Skye.

Beta version



Figure 9-4: Field view of feldspathic peridotite in the Layered Peridotite Series, Cuillin Intrusive Centre, An Garbh-choire, Skye. Pole *ca*. 1 m long.



Figure 9-5: Xenolithic and brecciated peridotites of the Layered Peridotite Series, Cuillin Intrusive Centre, An Garbh-choire, Skye.



Figure 9-6: Layered gabbros of the Outer Bytownite Gabbros, Cuillin Intrusive Centre, east of the Scavaig River, Cuillin, Skye. Pole *ca.* 1 m long.



Figure 9-7: Layered gabbros of the Inner Gabbros, Cuillin Intrusive Centre, Druim Hain, Cuillin, Skye. Pole *ca.* 1 m long.

Proof version

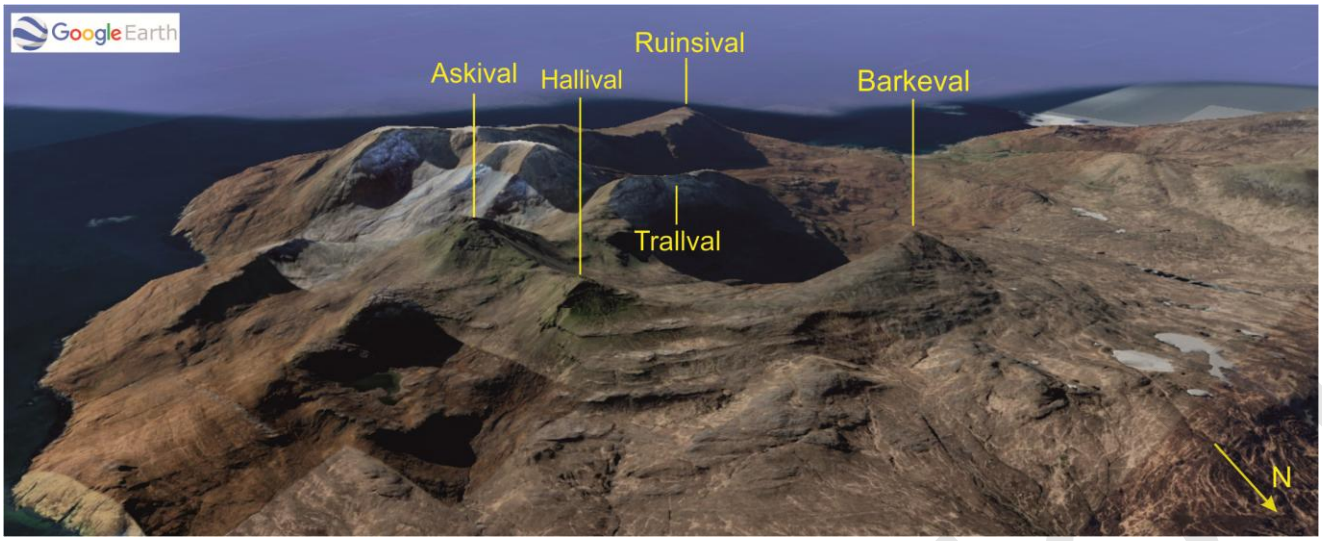


Figure 9-8: Oblique Google Earth© image of the glacially sculpted peaks of the Rum Central Complex, composed of peridotites, troctolites and gabbros.



Figure 9-9: Pale layered troctolites and dark peridotites of the Eastern Intrusion, Rum, forming the peak of Hallival, viewed towards the north from Askival towards the Cuillin, Skye.[Photograph courtesy of David Brown]

Beta Version



Figure 9-10: Dark peridotite breccia and pale layered troctolites of the Central Intrusion, Rum, at the southern end of Kilmory Glen, close to the track. Pole *ca.* 1 m long.



Figure 9-11: Pale layered troctolites of the Central Intrusion, Rum, at the southern end of Kilmory Glen, close to the track. Pole *ca.* 1 m long.



Figure 9-12: Troctolites of the Central Intrusion, Rum, with mineralogical 'grading' (dark olivine rich and pale plagioclase rich) at the southern end of Kilmory Glen, close to the track. Pole *ca*. 1 m long.



Figure 9-13: Blocks of layered bytownite troctolite and feldspathic peridotite in a breccia of bytownite troctolite, Central Intrusion, Rum, south of the Long Loch. Note the 'finger-structures' within some of the blocks.

Proof version

9.2.2 Basic cone-sheets and linear dyke swarms

Cone-sheet emplacement and its relationship with the linear dyke swarms (Chapter 7) have been examined by Walker (1975b, 1993b). Sets of cone-sheets, commonly of basalt and dolerite, form conical intrusions, each typically less than 5 m thick, with a common focal point at depth (Figure 9-14; Figure 9-15; Figure 9-16). They are generally more numerous in two opposing quadrants of the central complex, for example NW and SE, and are related to a dyke swarm that, in this example, would trend NW-SE.

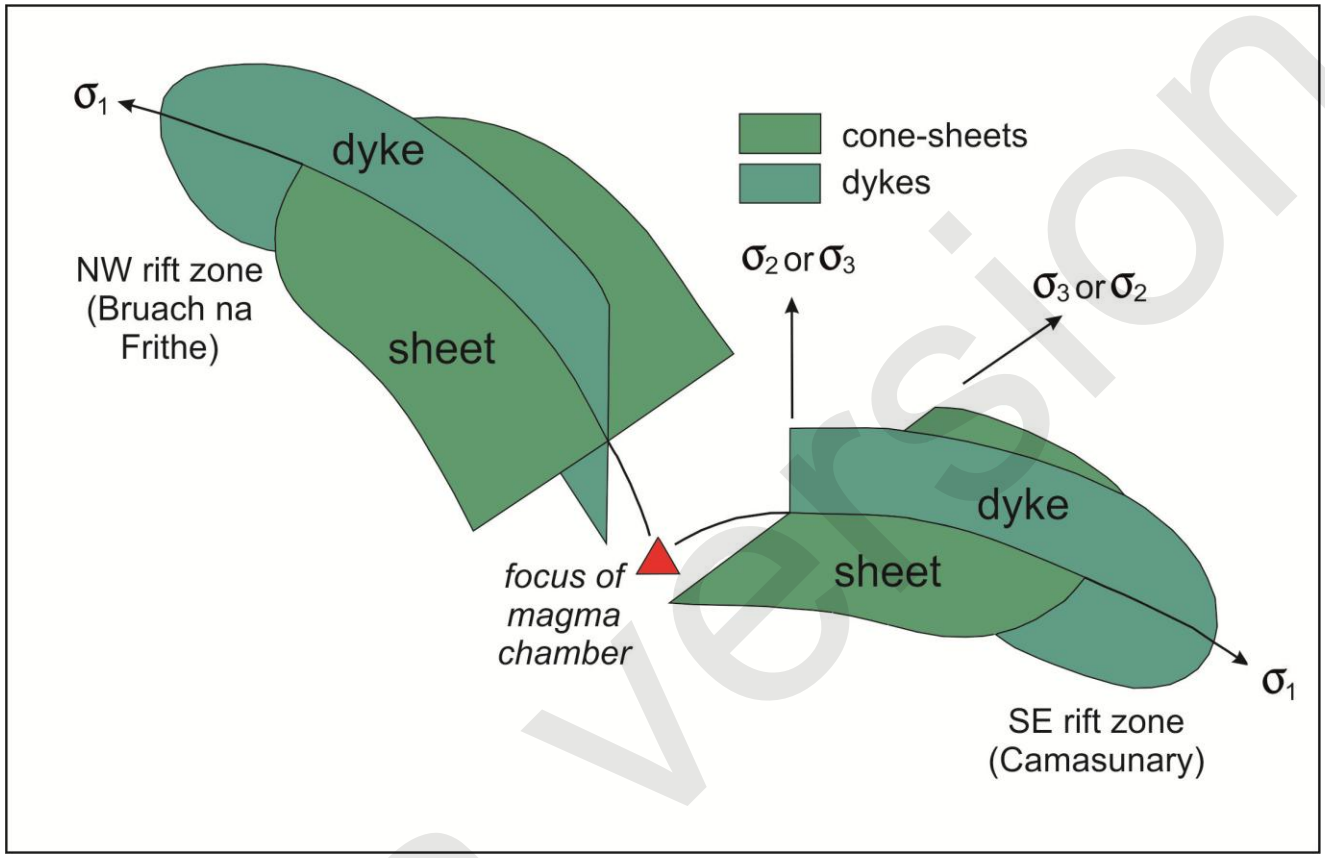


Figure 9-14: Relationship between cone-sheets and a dyke swarm. Dykes are injected when the principal deviatoric stress axis is horizontal, and cone-sheets are injected when the principal deviatoric stress axis is vertical (after Walker 1993b and Emeleus & Bell 2005).

Thus, the central complex appears to have acted as a focal point for cone-sheet and dyke emplacement. Detailed mapping of the cone-sheets and dykes indicates that the emplacement of both sets of intrusions overlaps in time and space. Where crustal dilation is slow, then magma excursions cannot be accommodated as dykes, but rather will be emplaced as cone-sheets. Intrusion of sets of cone-sheets can cause vertical thickening and uplift of the volcanic edifice by as much as 1,500 m (e.g. Le Bas, 1971), similar to the amount of horizontal crustal dilation resulting from the intrusion of some dyke swarms (Chapter 7).

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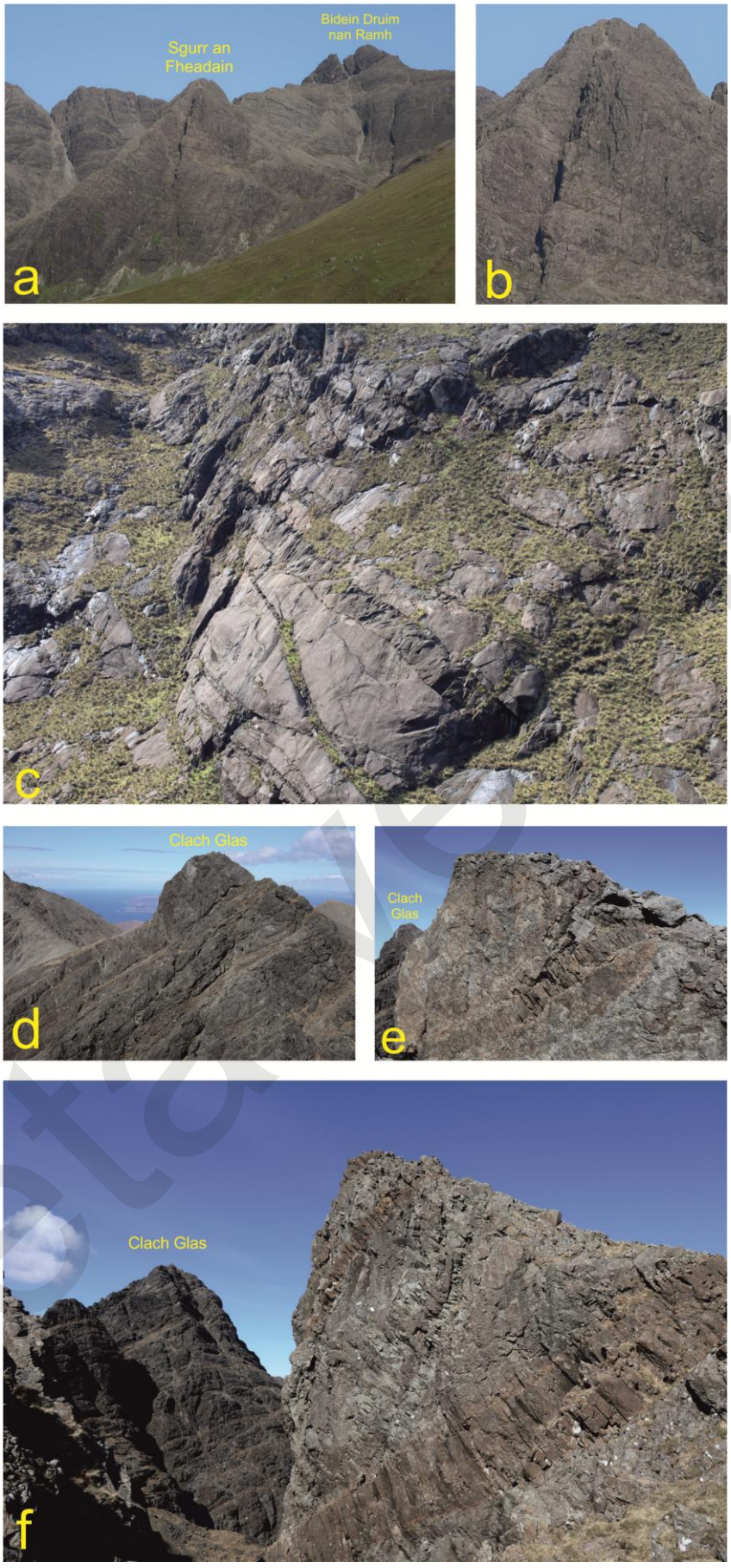


Figure 9-15: Basic (basalt and dolerite) cone-sheets and inclined sheets: (a) & (b), Sgùrr an Fheadain, NW Cuillin, Skye, a focus of cone-sheets and dykes; and (c) – (f) examples of cone-sheets within the Cuillin Intrusive Centre ((c) between the Scavaig River and the Bad Step; (d), (e) and (f), east of Blà-Bheinn).

Beta Version



Figure 9-16: Cone-sheets in Coir' a' Tairneilear, NW Cuillin, inclined towards the SE. The summit, top left, is Bidein Druim nan Ramh.

9.2.3 Intermediate, hybrid and granitic plutons

Intermediate, hybrid and granitic rocks typically occur in nested plutons, comprising small, stock-like intrusions, usually with steep-sided, outwardly-inclined margins, which are for the most part younger towards the core of the intrusive centre (Figure 9-17; Figure 9-18; Figure 9-19; Figure 9-20; Figure 9-21).

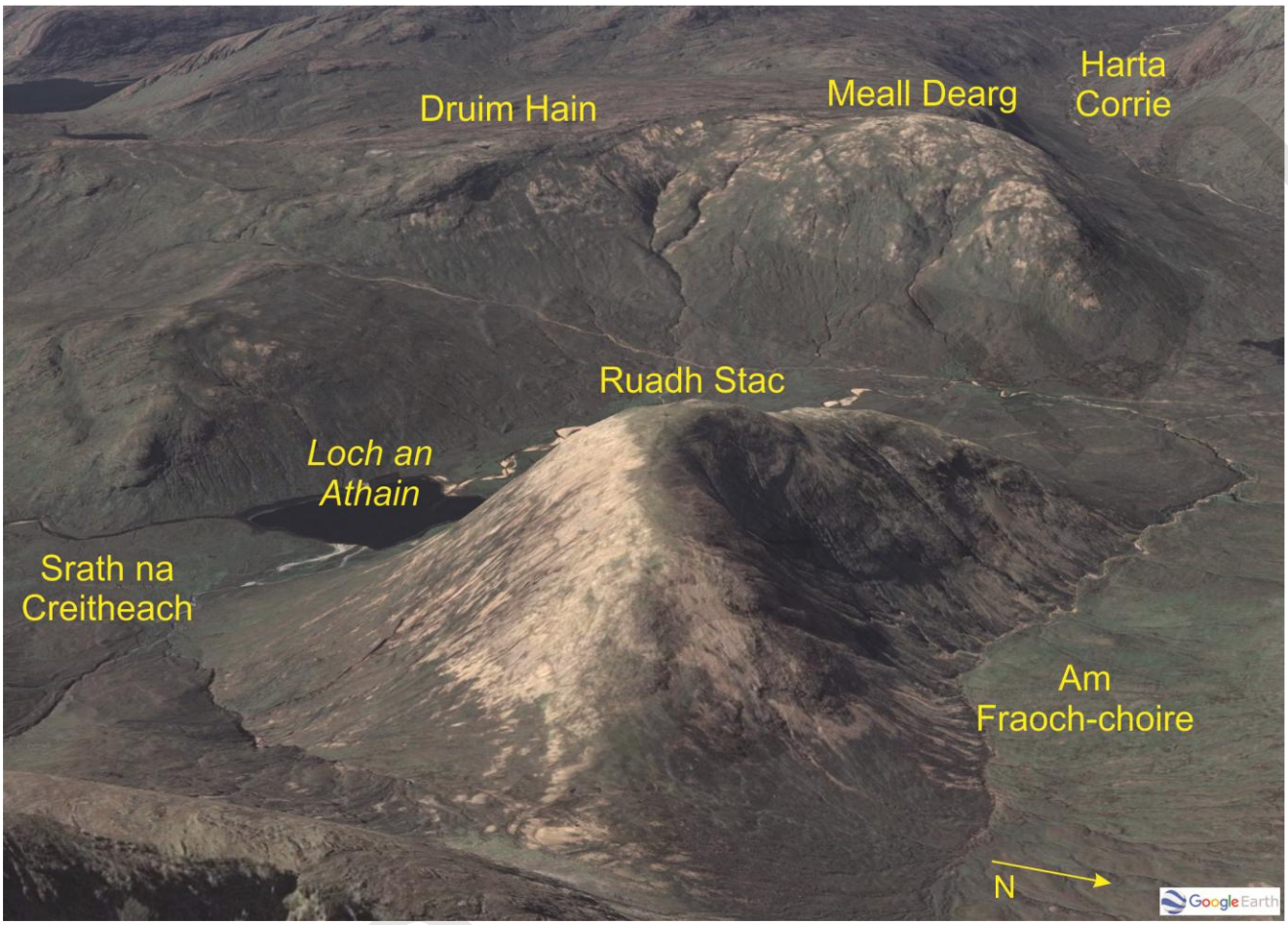


Figure 9-17: Oblique Google Earth© image of Ruadh Stac and Meall Dearg, composed of granites of the Srath na Crèitheach Intrusive Centre, Skye, which post-date gabbros on Druim Hain of the Cuillin Intrusive Centre.

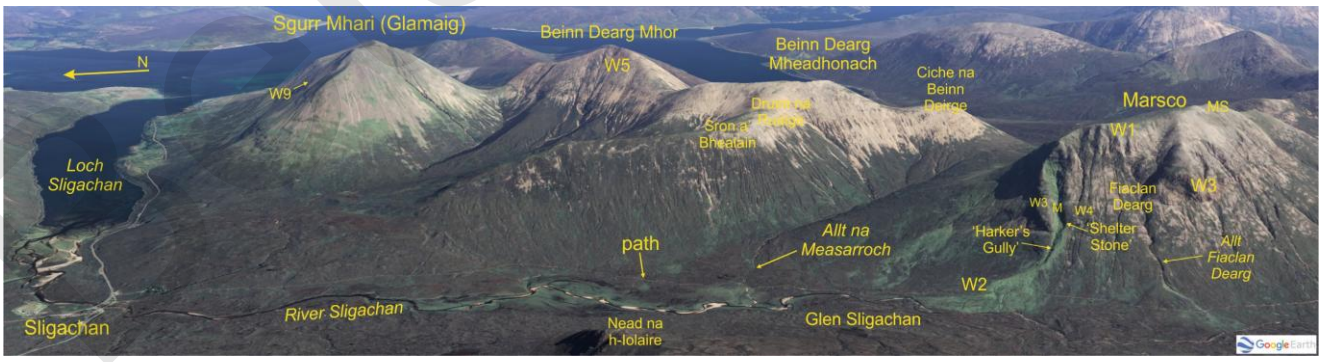


Figure 9-18: Oblique Google Earth© image of the Red Hills on the east side of Glen Sligachan, composed of various granites and hybrid rocks of the Western Red Hills Intrusive Centre, Skye.

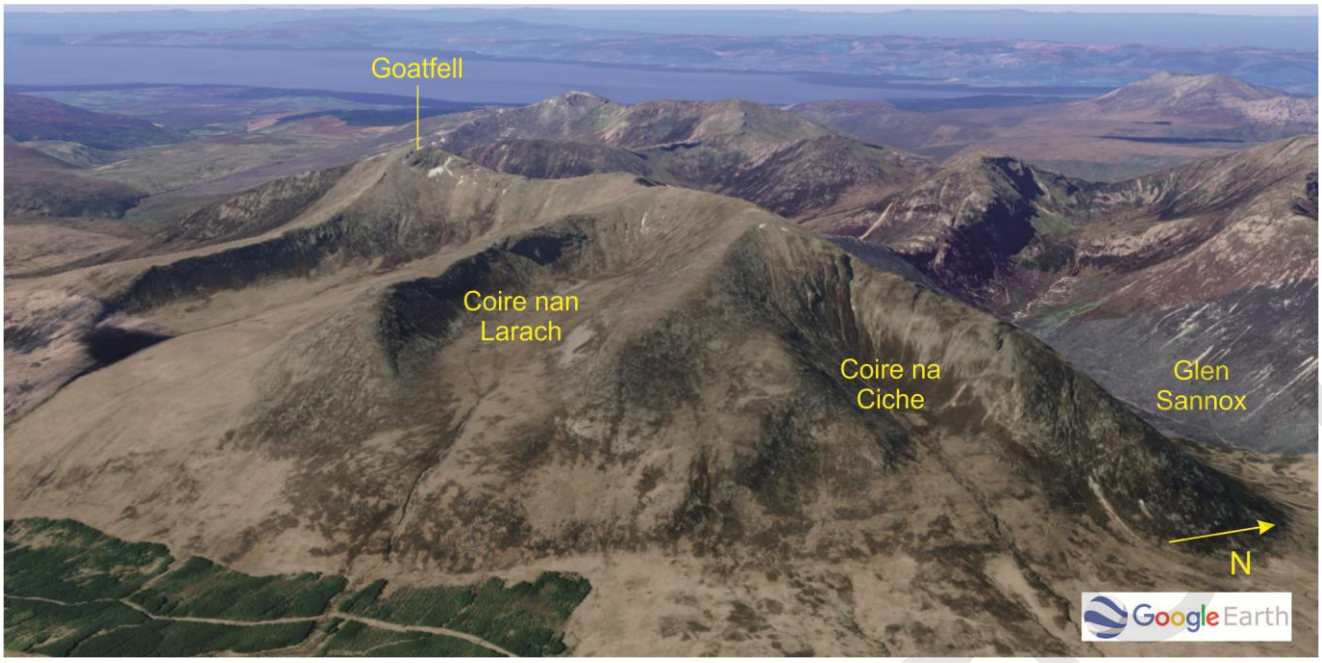


Figure 9-19: Oblique Google Earth© image of the summits composed of the North Arran Granite Pluton.



Figure 9-20: The rugged, glaciated skyline of the western summits of North Arran Granite Pluton, viewed from the northern end of Glen Rosa.

Beta version



Figure 9-21: Fin(er)-grained, biotite-bearing Inner Granite of the North Arran Granite Pluton, typical of many granites of the Hebridean Igneous Province. Coin *ca.* 24 mm across.

9.2.4 Ring-dykes

Ring-dyke emplacement occurs when silicic magma is intruded along steep, outwardly dipping fractures resulting from the subsidence of a central, cylinder-like block. The fractures may either reach the Earth's surface, forming a caldera and initiating surface volcanism, or be truncated along a subsurface, planar and essentially horizontal fracture, resulting in a cauldron subsidence, with little or no volcanism (Figure 9-22). Associated with the central subsidence process, the silicic magma(s) may create space by stoping and by gas brecciation during their ascent. Ring-dykes commonly occur in nested sets with complicated intrusive relationships, as exemplified by the Mull and Skye central complexes (Figure 9-23; Figure 9-24; Figure 9-25; Figure 9-26).

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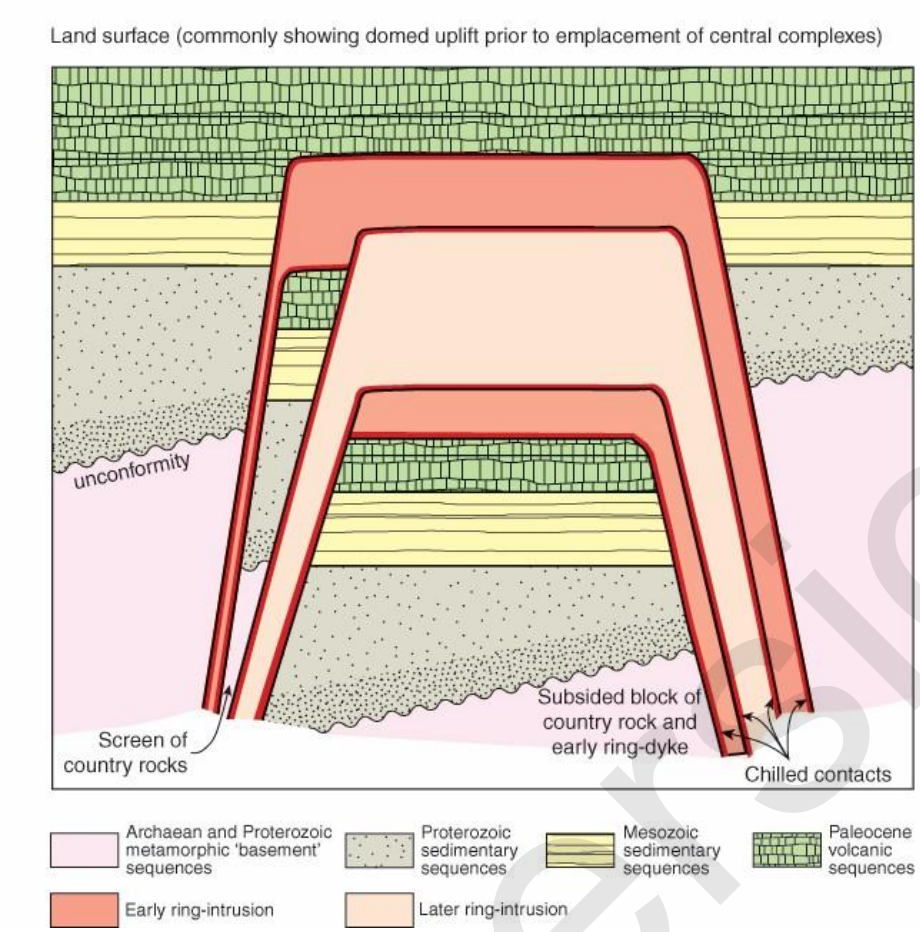


Figure 9-22: Form and mode of occurrence of ring-dykes (after Richey 1932).

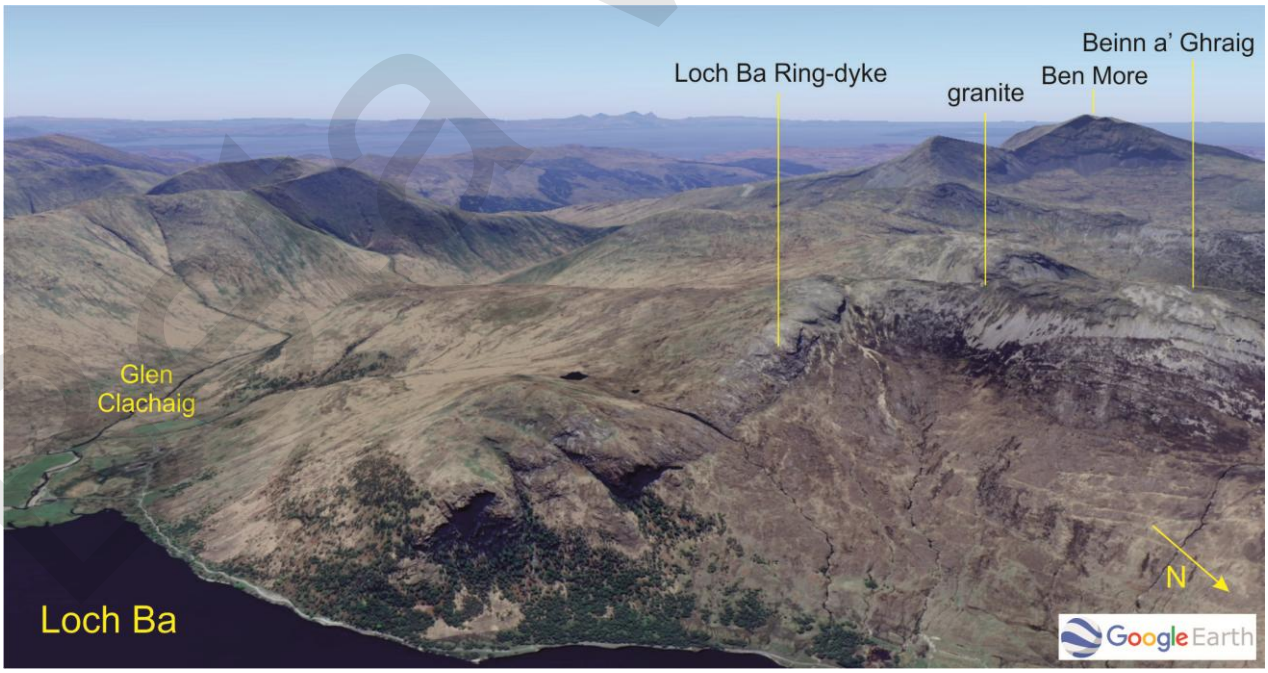


Figure 9-23: Oblique Google Earth© image of the Loch Bà Ring-dyke, a hybrid ('mixed-magma') intrusion within the Mull Central Complex.

Draft version



Figure 9-24: The Loch Bà Ring-dyke, forming the prominent ridge in the middle ground. View towards the SE from Beinn a' Ghràig. [Photograph courtesy of Ian Williamson]



Figure 9-25: Detail of the Loch Bà Ring-dyke, a mixed-magma intrusion comprising wisp- and bleb-like mafic inclusions within the dominant felsite/rhyolite. Coin *ca*. 21 mm across.

PREVIEW VERSION

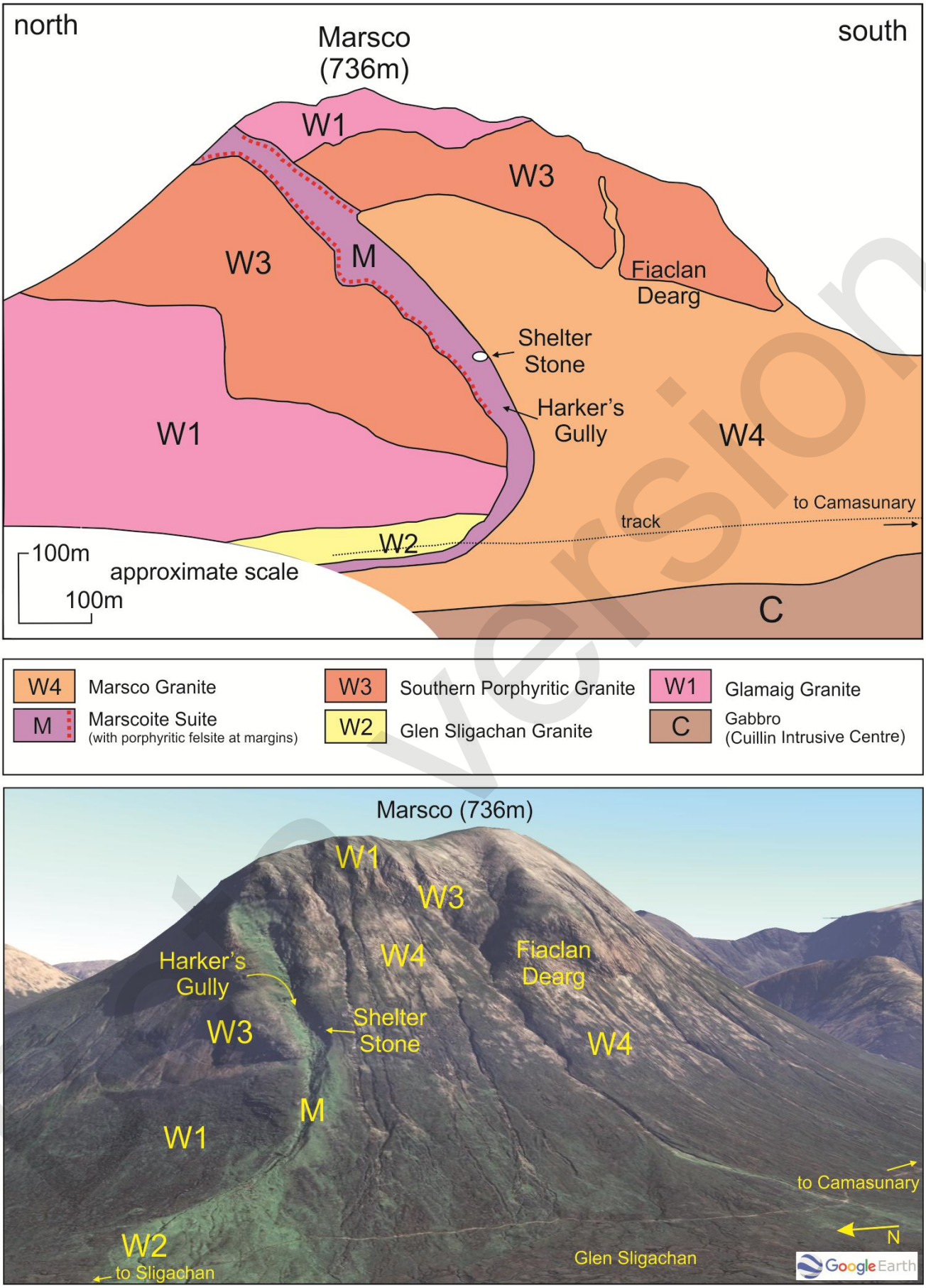


Figure 9-26: Oblique Google Earth© image and schematic representation of the various granitic and hybrid rocks of the Western Red Hills Intrusive Centre, Skye, exposed on Marsco at the southern end of Glen Sligachan, including the Marscoite Suite, composed of granitic and hybrid ('mixed magma') units.

Pre-publication version

Evidence for volcanic activity during the development of the central complexes, much of it likely to have been associated with ring-dyke emplacement (Figure 9-27; Figure 9-28) and covering a wide range in composition, may be caught up as screens between younger intrusions (Figure 9-22). The amount of such evidence varies, but this may simply reflect the relative level of erosion. For example, at the present day, the rocks exposed in the Central Arran Ring-complex are predominantly lavas and volcaniclastic rocks, with minor amounts of gabbro, granite and other coarse-grained rocks, but it is likely that with further erosion these proportions would be reversed and eventually the volcanic rocks would be removed (Figure 9-29; Figure 9-30). Surface venting would appear to have been more common during the earlier stages of development of individual central complexes.



Figure 9-27: Silicic ignimbrite, Meall Breac, Rum. Compass *ca.* 10.cm long.



Figure 9-28: Stratified volcaniclastic sandstone within a sequence of massive volcaniclastic breccias, Glendrian Caves, Rubha Carrach, north Ardnamurchan. Pole *ca.* 1 m long.

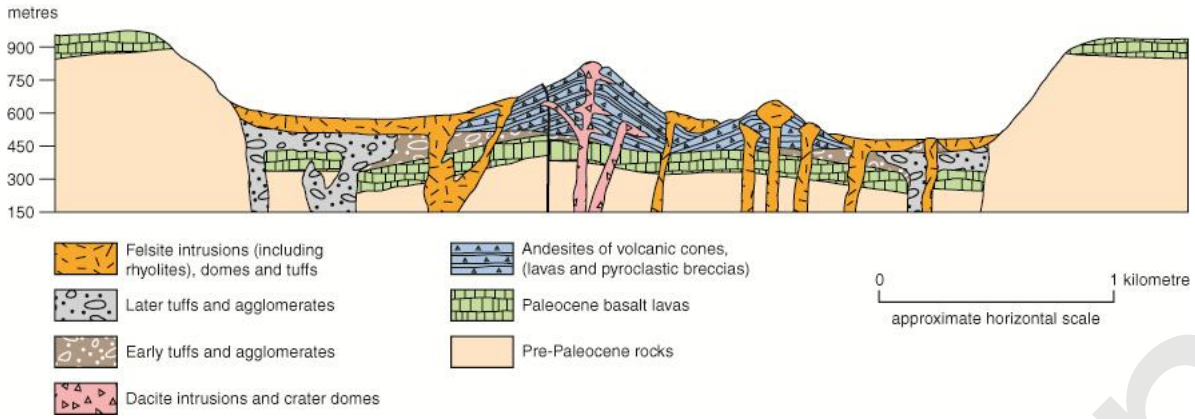


Figure 9-29: Diagrammatic cross-section showing the inferred structure of the Central Arran Ring-complex, prior to erosion. The section is only approximately to scale and schematic, but the main cone may be regarded as representing Ard Bheinn (after King 1955).

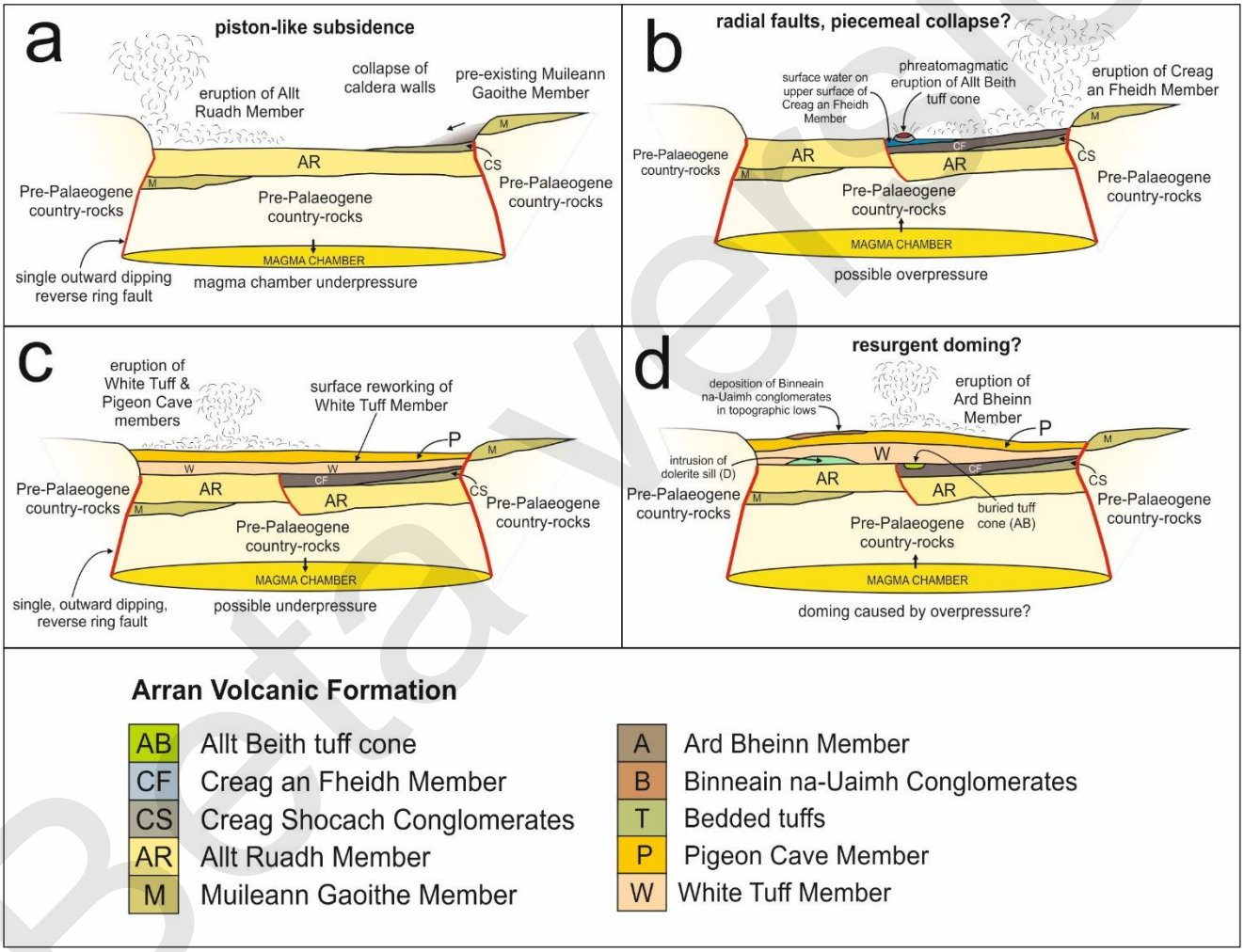


Figure 9-30: A series of generalised cross sections through the Arran Volcanic Formation (Central Arran Ring-complex) showing the history of eruption and caldera collapse. Lithologies other than the caldera-fill succession have been omitted for clarity (after Gooday *et al.* 2018).

Beta version

9.3 Alteration processes and deformation of country-rocks

Intrusion of magma into the upper, water-saturated crust resulted in the development of convecting hydrothermal systems that circulated meteoric water through both the intrusions and the adjacent country-rock (Figure 9-31). This resulted in pervasive low-grade alteration that is estimated to have taken place at *ca*. 400°C and caused alteration of mafic minerals, generating 'serpentine' from olivine, and amphibole and chlorite from pyroxene and biotite. Alteration of silicic minerals resulted in turbidity and clay-mineral formation in feldspars, and fluid inclusion development in quartz. Where fluid flow was more focussed, secondary precipitation of minerals such as chlorite, epidote, prehnite and carbonate occurred in the myriads of tensile fractures that developed in response to both cooling of the intrusions and fracture by fluid ingress (Figure 9-32).

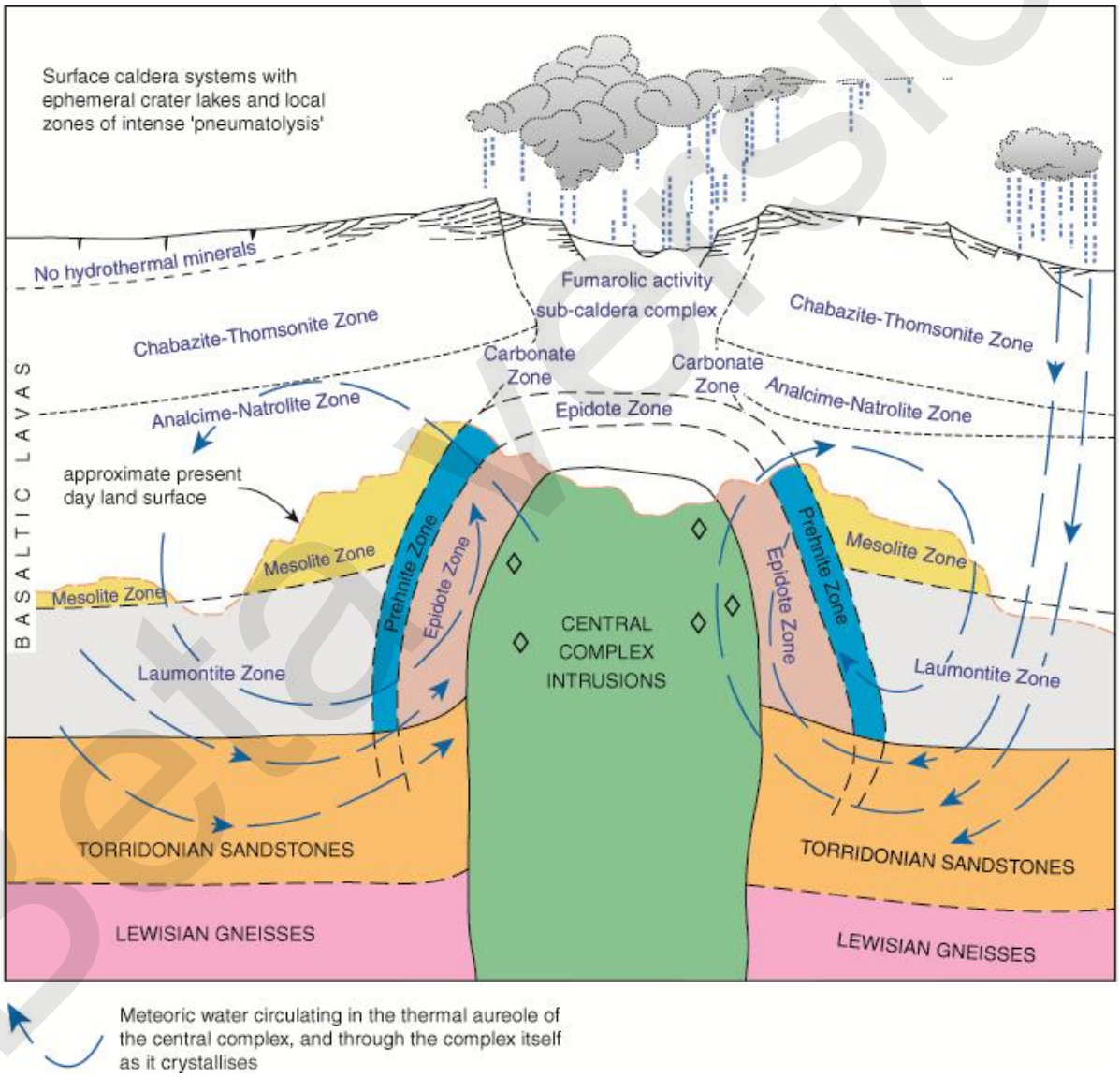


Figure 9-31: A diagrammatic cross-section showing the hydrothermal mineral zones in the lavas and the superimposed alteration zones developed about the Mull Central Complex in response to the circulation of heated meteoric water (after Walker 1971).

Beta version



Figure 9-32: Hornfelsed basaltic lava on the west side of the Abhainn Camas Fhionnairigh, SE Cuillin, Skye, with abundant veins containing numerous secondary hydrothermal minerals, including epidote, chlorite, various zeolites and carbonates. Hammer *ca*. 30 cm long.

The heated meteoric waters also imparted distinctive stable isotopic signatures to the altered rocks; these are useful in determining the origin of the water and in tracing the circulation patterns (e.g. Taylor & Forester 1971; Forester & Taylor 1976, 1977). The pervasive alteration haloes that formed extend laterally for as much as 20 km from the margins of the central complexes, as on Mull, but the most intense alteration that was caused by temperatures in excess of 800°C is restricted to a zone less than 1 km in width, in places much less. The mineral-filled fractures are more localised, either within the central complexes or in narrow zones in the surrounding country-rocks that are commonly NW-trending, parallel to the regional dyke swarms. Within the lava piles intruded by the Mull and Skye central complexes, the narrow concentric zones of secondary mineral growth that are attributed to the emplacement of the central complexes are superimposed on flat-lying zeolite and other mineral zoning that resulted from burial metamorphism of the lavas (Walker 1971). The pervasive alteration of rocks in and surrounding the central complexes by circulating hydrothermal systems is a potential cause for the change to rock chemistry and careful sampling is necessary when fresh material is required for geochemical and isotopic studies (e.g. Pankhurst *et al*. 1978; Walsh *et al*. 1979; Dickin & Exley 1981).

The deformation of the surrounding country-rocks during emplacement, and possibly because of central uplift and gravitational collapse, has led to the development of spectacular annular folds (Figure 9-33), which extend outwards for distances of up to 5 km from the central complexes and produce significant upper crustal shortening (Chapter 11).

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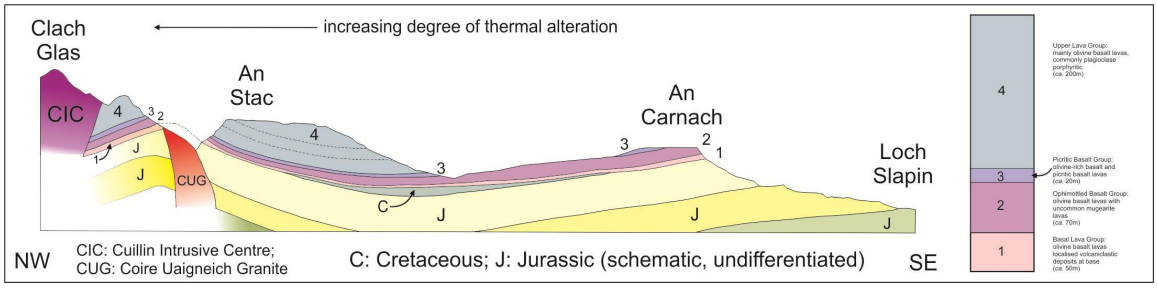


Figure 9-33: Syncline within lavas to the east of the Cuillin Intrusive Centre on Strathaird (after Almond 1964).

The most complete example occurs around the margin of the Mull Central Complex, where folding of pre-Palaeozoic country-rocks may have commenced prior to the eruption of the Mull Lava Group (Chapter 6), which predated the central complex (Walker 1975a). Within the area of the central complex, the lavas unconformably overlie metasedimentary basement rocks of the Moine Supergroup (Chapter 2) or on Triassic sedimentary rocks (Chapter 3). In contrast, at the margins of the updomed area, they overlie Jurassic and Cretaceous sedimentary rocks (Chapter 3).

9.4 Central uplift, unroofing and subsidence

Central uplift of several hundreds of metres occurred during the emplacement of the layered ultrabasic and basic units and the predominantly basic cone-sheet sets, for example on Skye and Mull. This uplift may have been very rapid and possibly led to very early unroofing of some of the central complexes, for example, Rum. Emplacement of granites also caused central uplift, as in north Arran, where there are steep-sided domes. However, where fracture systems penetrated to the contemporaneous land surface, as on Rum, emplacement of silicic magmas was commonly accompanied by central subsidence, with caldera formation and associated volcanic eruptions (Figure 9-27).

Central collapse, possibly by several hundreds of metres, would have accompanied the emplacement of ring-dykes, many of them being of the 'mixed-magma' type, such as the Loch Bà Ring-dyke on Mull (Figure 9-25), the Marsco Ring-dyke in the Western Red Hills Centre of Skye (Figure 9-26), and the Sgùrr nam Meann Ring-dyke of Centre 2, Ardnamurchan (Figure 9-34), although these examples do not preserve direct evidence of associated volcanicity.



Figure 9-34: Intrusion breccia of quartz dolerite net-veined by granophyric microgranite in the Sgùrr nam Meann Ring-dyke of Centre 2 of the Ardnamurchan Central Complex at Eilean Carrach. Coin *ca.* 24 mm across.

Beta version

9.5 Geophysical signatures

Gravity and magnetic anomalies are associated with the central complexes. All the complexes are characterised by positive Bouguer gravity anomalies which are generally large, very localised and characterised by steep gradients (Figure 9-35; Figure 9-36)



Figure 9-35: Gravity anomaly image of western Scotland: Bouguer anomalies onshore and free-air anomalies offshore. Colour shaded-relief image is illuminated from the NW: red = high, blue = low. Superimposed contours are at 10 mGal intervals. The Paleocene central complexes are characterised by strong circular positive anomalies up to 50 km in diameter, indicating the presence of localised masses of dense ultrabasic and basic rocks high in the Earth's crust (from Emeleus & Bell 2005).

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The geophysical anomalies are attributed to the presence of steep-sided bodies of dense rock, such as gabbro or peridotite, extending to depths of 15 km or more (McQuillin & Tuson 1963; Bott & Tuson 1973; but see also Emeleus *et al.* 1996b). Based upon these geophysical data, it is inferred that where granites dominate the present-day surface outcrop, they are thin and do not extend to depth (Figure 9-36). For example, for Mull, Bott & Tantrigoda (1987) estimated that granitic rocks form as little as 10 per cent by volume of the entire complex and are less than 2 km thick. Supporting evidence comes from seismic investigations carried out over the Western Red Hills Intrusive Centre on Skye, where it is inferred that the granites are about 2 km thick and overlie interleaved basic and silicic sheets located at depths of between 2,100 and 2,400 m (Goulty *et al.* 1992).

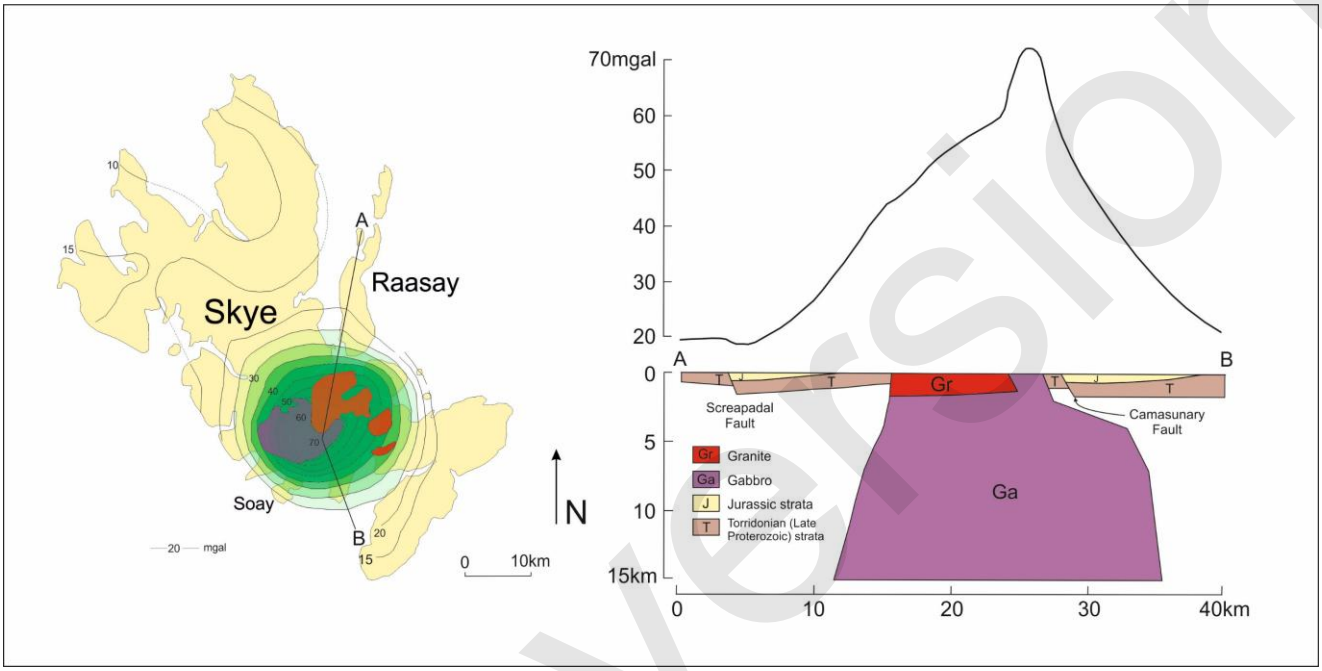


Figure 9-36: Interpretation of the subsurface structure of the Skye Central Complex based upon gravity data (after Bott & Tucson 1973).

Strong, comparatively localised magnetic anomalies over the complexes most likely reflect the predominance of gabbroic rocks; such magnetic anomalies are due to the presence of high modal amounts of iron-titanium oxides, which are generally only sparsely present in rocks more primitive than gabbro (e.g. peridotite and troctolite). Local aerial magnetic data provide further insights regarding the nature of the postulated cylinder of mafic and ultramafic rock below the Skye Central Complex (SCC) (Brown & Mussett 1976). In simple terms, the magnetic signature for the area over the outcrop of the Cuillin Intrusive Centre (CIC) is negative, with values as low as -250 nT, whereas the signature over the outcrop of the Red Hills granites is positive, up to +250 nT (Figure 9-37). The granites, however, are not likely to have significantly contributed to the magnetic signature. Thus, the cylinder of basic/ultrabasic rocks modelled to explain the gravity anomaly has (at least) two discrete units or components, each acquiring their magnetic signature as they cooled through the Curie Temperature for magnetic minerals such as magnetite (500-600 °C). The mass below the CIC was emplaced and cooled through the Curie Temperature when the Earth's magnetic field was negative, whereas the mass below the Red Hills cooled whilst the Earth's magnetic field was positive/normal. Field relationships indicate clearly that the positive polarity event was after the negative polarity event. Thus, at least two significant and discrete bodies of mafic/ultramafic magma were emplaced at depth during the lifetime of the SCC and bridged a time when the Earth's magnetic field reversed.

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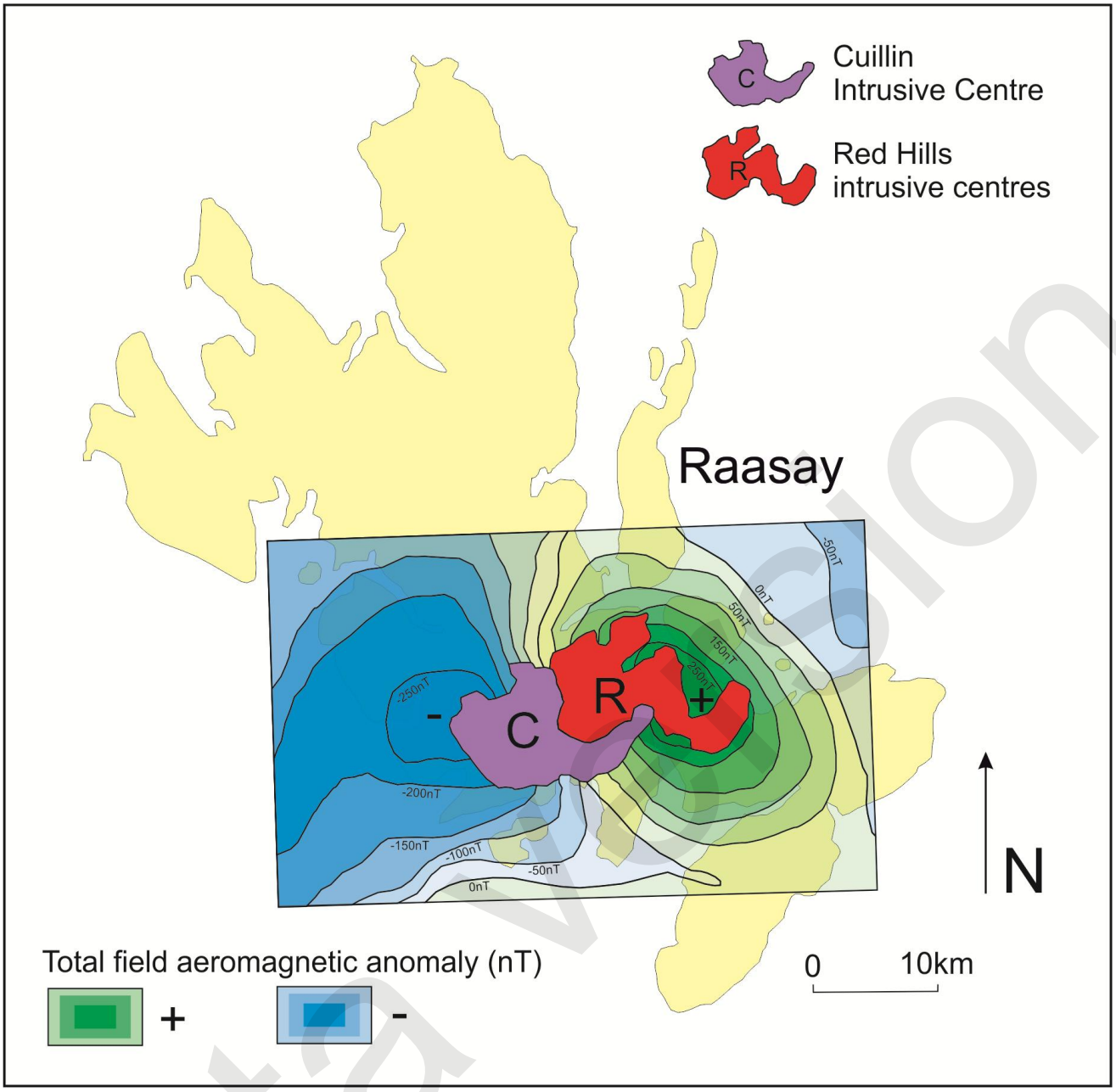


Figure 9-37: Aeromagnetic data for the outcrop area of the Skye Central Complex, with discrete negative and positive signatures inferring two events that straddle a magnetic polarity reversal (negative, then positive) (after Brown & Mussett 1976).

Some twenty-five other igneous centres or central complexes have been identified throughout the continental shelf north and west of the Outer Hebrides from geophysical surveys (Figure 9-38). Some are exposed on the seabed and have been sampled, but others are concealed by younger strata. Their features are summarised by Fyfe *et al.* (1993) and by Stoker *et al.* (1993).

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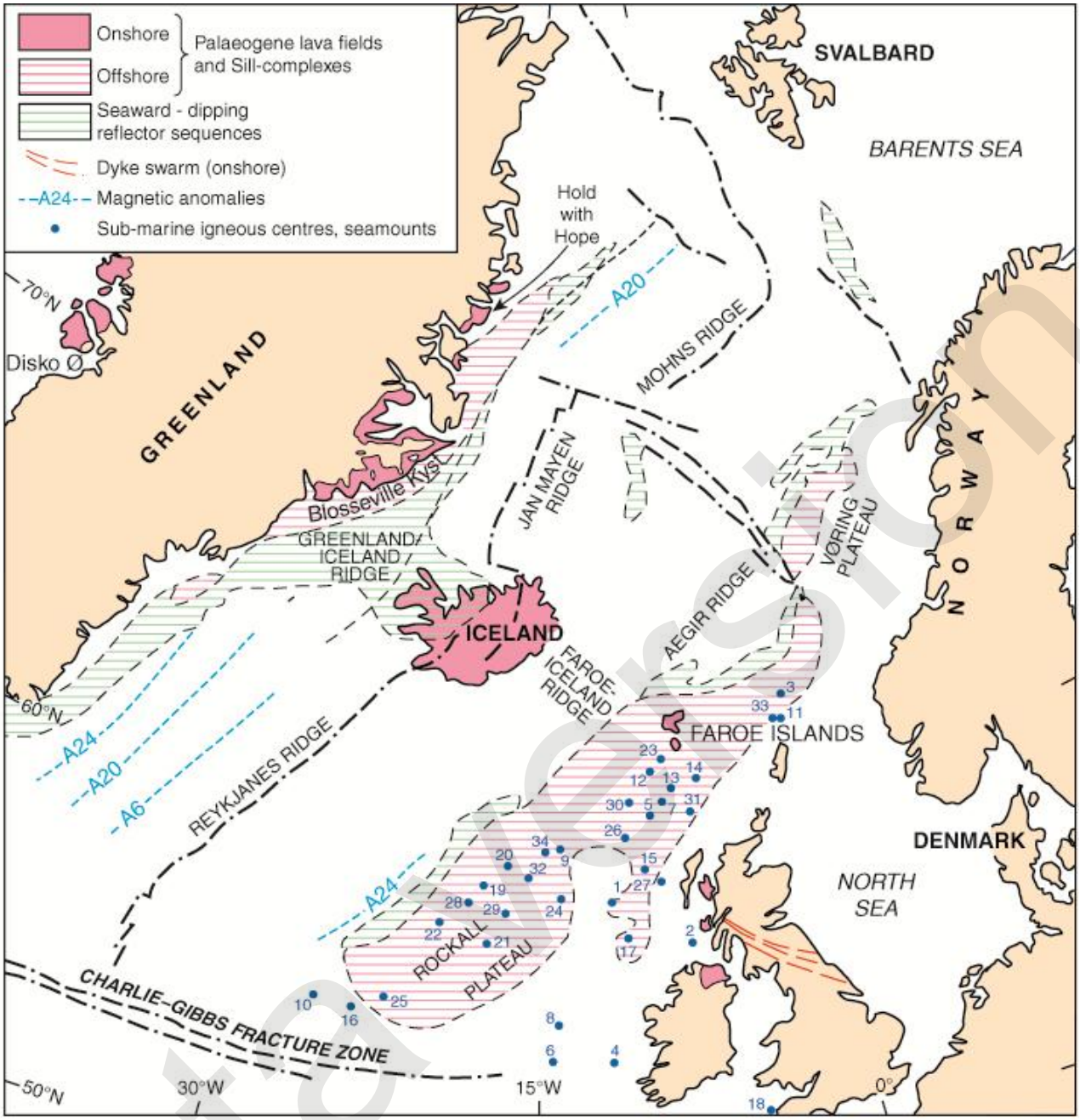


Figure 9-38: The North Atlantic Igneous Superprovince showing the extent of onshore and offshore igneous activity (modified after Saunders *et al.* 1997).

The onshore complexes are described from north to south in Section 9.6, below. The submerged Blackstones Bank Central Complex is also described.

Beta version

9.6 St Kilda Central Complex

The St Kilda archipelago comprises a group of precipitous islands and islets consisting entirely of Paleocene intrusive igneous rocks that form a central complex close to the edge of the continental margin (Figure 9-39; Figure 9-40; Figure 9-41) (Harding 1966, 1967; Harding *et al.* 1984; Stoker *et al.* 1993). Although no Pre-Paleocene rocks are found above sea level, Lewisian gneisses crop out on the surrounding seabed. Detrital minerals characteristic of regional and thermal metamorphic rocks occur in stream sediments on Hirta, washed out of drift deposits (Chapter 13). The central complex is the site of a strong positive Bouguer gravity anomaly, and the igneous rocks are reversely magnetised, most likely during the magnetic interval C26R. The principal intrusive units comprising the varied geology of Hirta, the largest island, are described below in order of their emplacement.

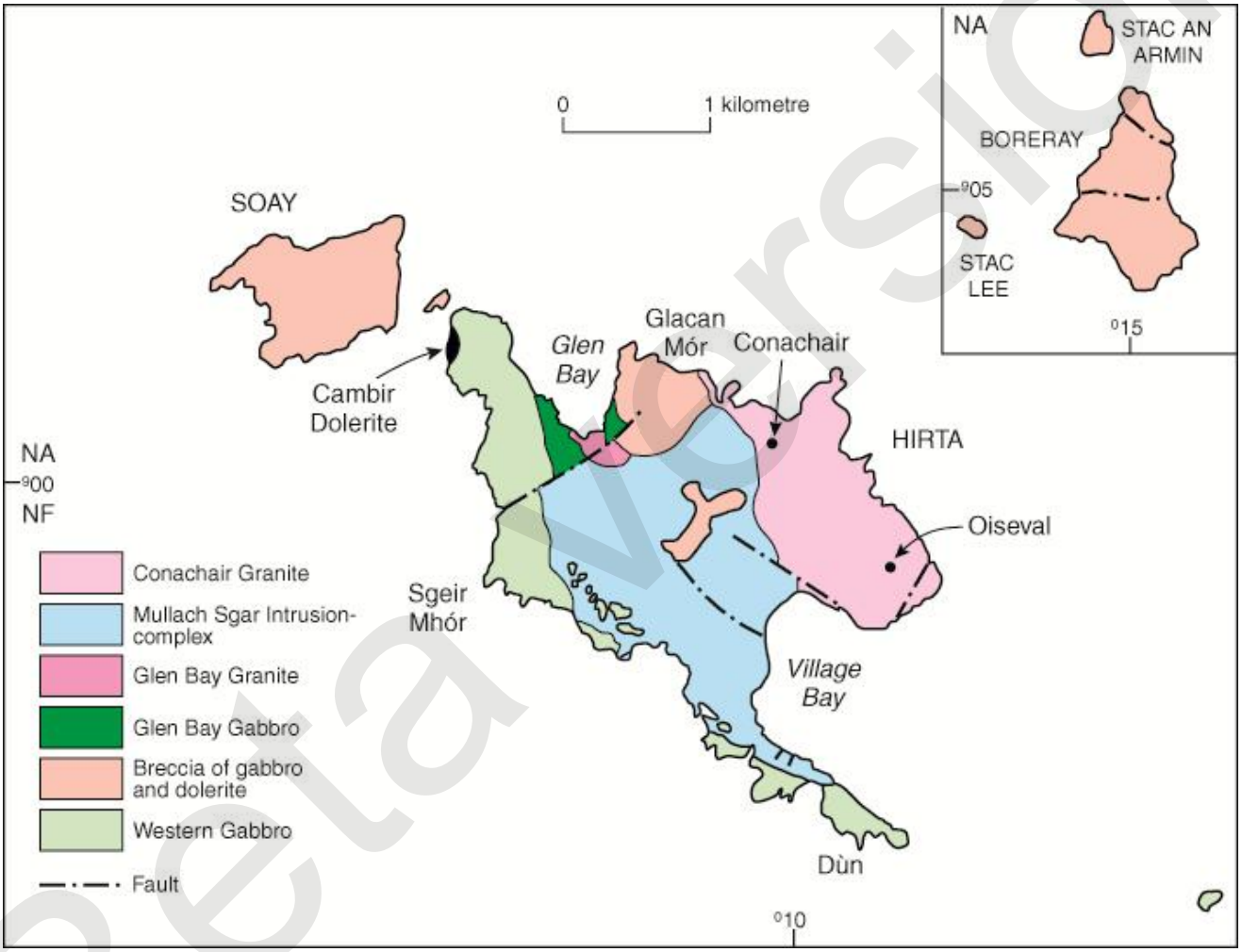


Figure 9-39: Geological map of the St Kilda Central Complex (after Harding *et al.* 1984).

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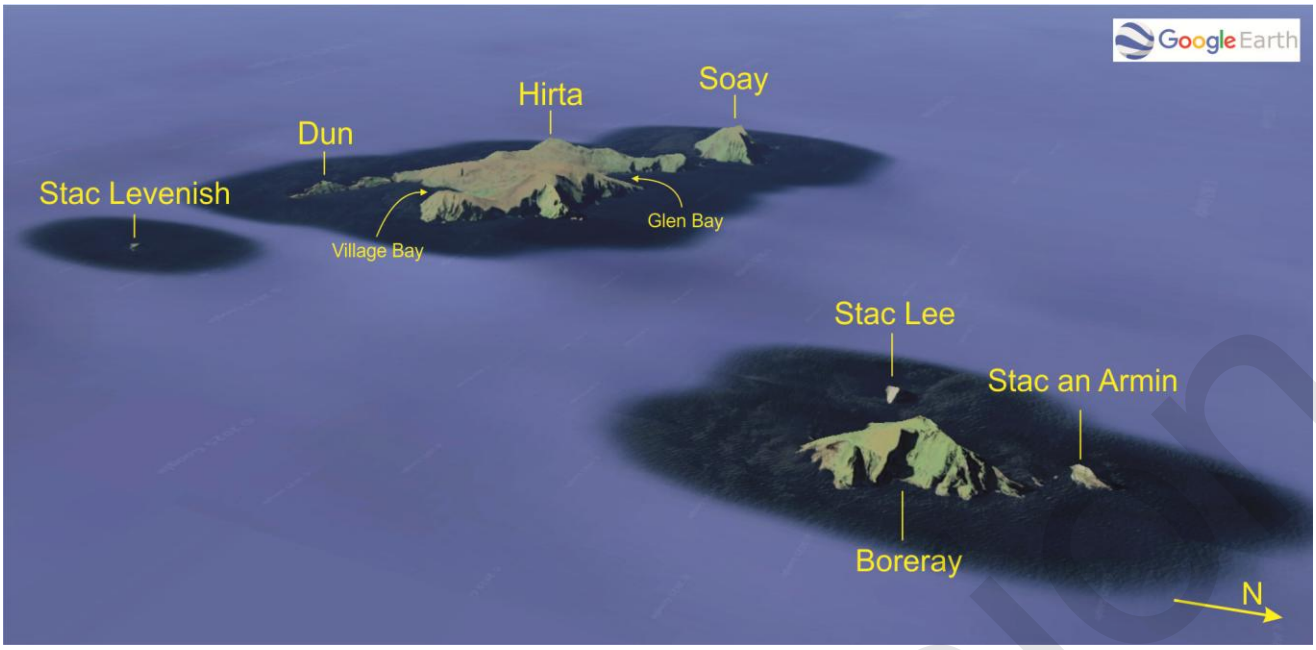


Figure 9-40: Oblique Google Earth© image of the St Kilda archipelago.



Figure 9-41: Cliffs of Boreray, composed of the 'Breccia of Gabbro and dolerite'.

The Western Gabbro is a texturally variable olivine-gabbro (Figure 9-42; Figure 9-43). An equigranular variant exhibits streaky banding, which reflects variations in modal mineral concentrations. A second type is characterised by large black augite crystals (*ca*. 2 cm across) containing numerous small white plagioclase crystals, which impart a characteristic speckled appearance to weathered surfaces. A third variety has a particularly marked textural range; in addition to containing elements of the first two types, there are pyroxene-rich and porphyritic facies and the rocks are commonly layered due to variation in both texture and mineral proportions. The dip of this layering, while locally variable, is general easterly to north-easterly, at *ca*. 45°. These gabbros may originally have formed part of a large, layered intrusion. Gabbro identical to some of the variants in the Western Gabbro occurs (with other gabbros) as blocks in the extensive breccias described below, which therefore postdate the Western Gabbro. On the north end of Hirta, a concentration of fine-grained, olivine–dolerite sheets intruding the Western Gabbro is referred to as the Cambir Dolerite.

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Figure 9-42: Dùn, composed of the Western Gabbro. View towards the SW from the east side of Hirta.



Figure 9-43: Dùn, composed of the Western Gabbro. View towards the SE from Hirta, with Stac Levenish in the distance.

Breccias of gabbro and dolerite crop out at Glacan Mor on Hirta, and on Boreray and Soay; they also form numerous islets and stacks (Figure 9-44; Figure 9-45; Figure 9-46; Figure 9-47; Figure 9-48). These spectacular breccias are made of large blocks of coarse-grained gabbro, commonly sheared, which are fragmented, veined and enclosed by dolerite. Similar brecciated gabbros have been recovered from the seabed between the main islands.

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Figure 9-44: Stac an Armin (left), Stac Lee (centre) and Boreray (right and largest island), composed of the Breccia of Gabbro and dolerite. [Photograph courtesy of David Brown]

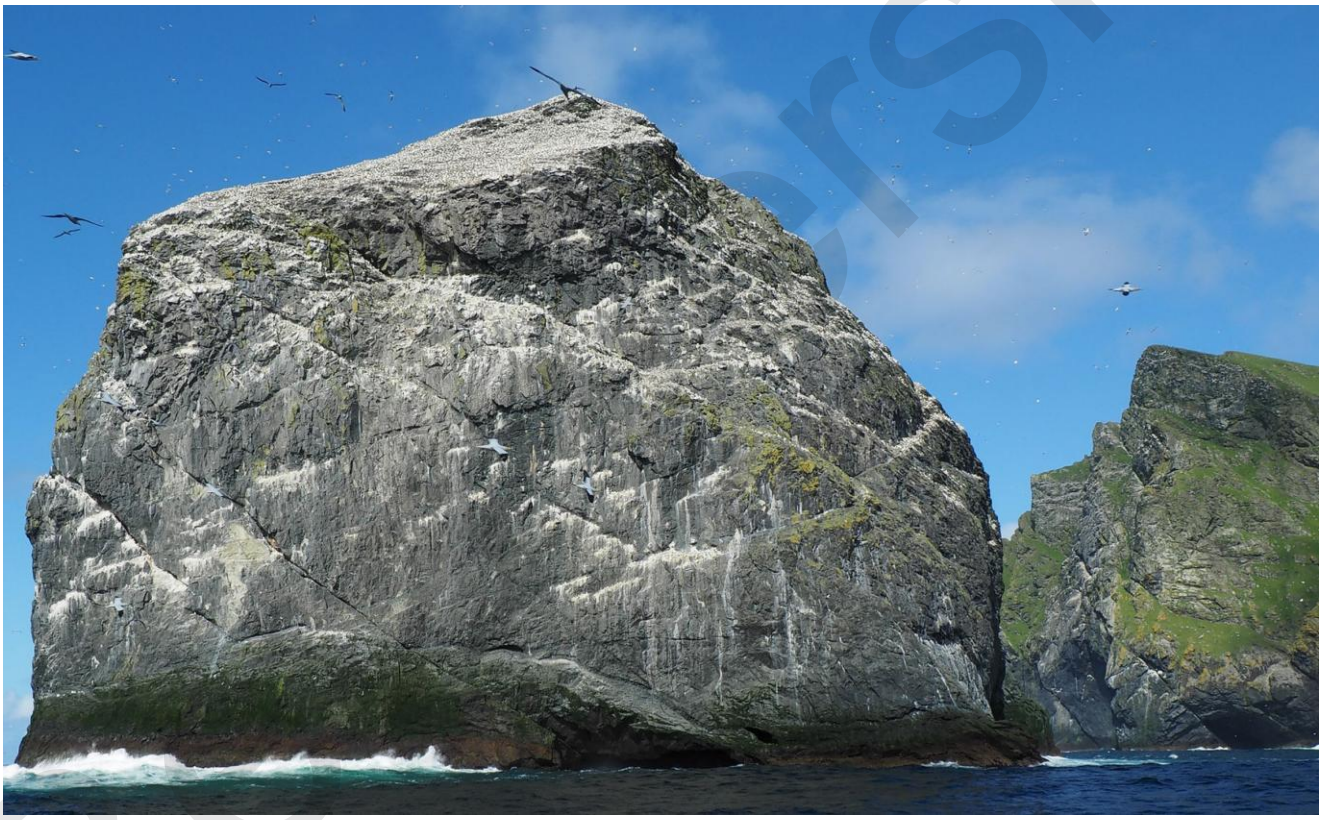


Figure 9-45: Stac Lee, composed of the Breccia of Gabbro and dolerite.

Beta version



Figure 9-46: Cliffs of Boreray, composed of the Breccia of Gabbro and dolerite.



Figure 9-47: Cliffs of Boreray, composed of the Breccia of Gabbro and dolerite. [Photograph courtesy of Ian Williamson]

Beta version



Figure 9-48: Cliffs of Boreray, composed of the Breccia of Gabbro and dolerite.

The Glen Bay Gabbro is an olivine-gabbro that crops out on both sides of Glen Bay and differs chemically from the older Western Gabbro. The age relationship is established by coarse-grained gabbroic veins, most likely derived from the Glen Bay Gabbro, which cut sheared parts of the Western Gabbro. On the eastern side of Glen Bay, the Glen Bay Gabbro has a black, splintery chilled margin against the Brecciated gabbros and dolerites of Glacan Mòr, in which glass extends for about 10 mm from the contact.

The Glen Bay Granite is medium-grained, granophyric in places, and contains micro-phenocrysts of zoned plagioclase. Ferroaugite and ferropigeonite are variably replaced by amphibole. The rare-earth-bearing, titanium-rich silicate chevkinite is an accessory mineral. The granite is fine grained (most likely chilled) adjacent to the Glen Bay Gabbro, and both have been affected by shearing.

The Mullach Sgar Intrusion-complex is one of the most distinctive rock assemblages in the St Kilda Central Complex (Figure 9-49). It comprises an extremely complicated assemblage of microgranite, microdiorite and dolerite sheets, dykes and igneous breccias. At least four generations of dolerite and microgranite intrusion are recognised and there is abundant evidence for the co-existence and mingling of silicic and basic magmas. Some of the most spectacular examples of this mingling and mixing phenomenon in the Hebridean Igneous Province are provided by the pillow-like masses of dolerite and basalt enclosed by microgranite, against which the basic rocks have developed fine-grained, glassy selvedges. Components of the Mullach Sgar Intrusion-complex intrude the Western Gabbro and enclose blocks derived from it; similar material intrudes the Glen Bay Granite and the gabbro and dolerite breccias in north Hirta.

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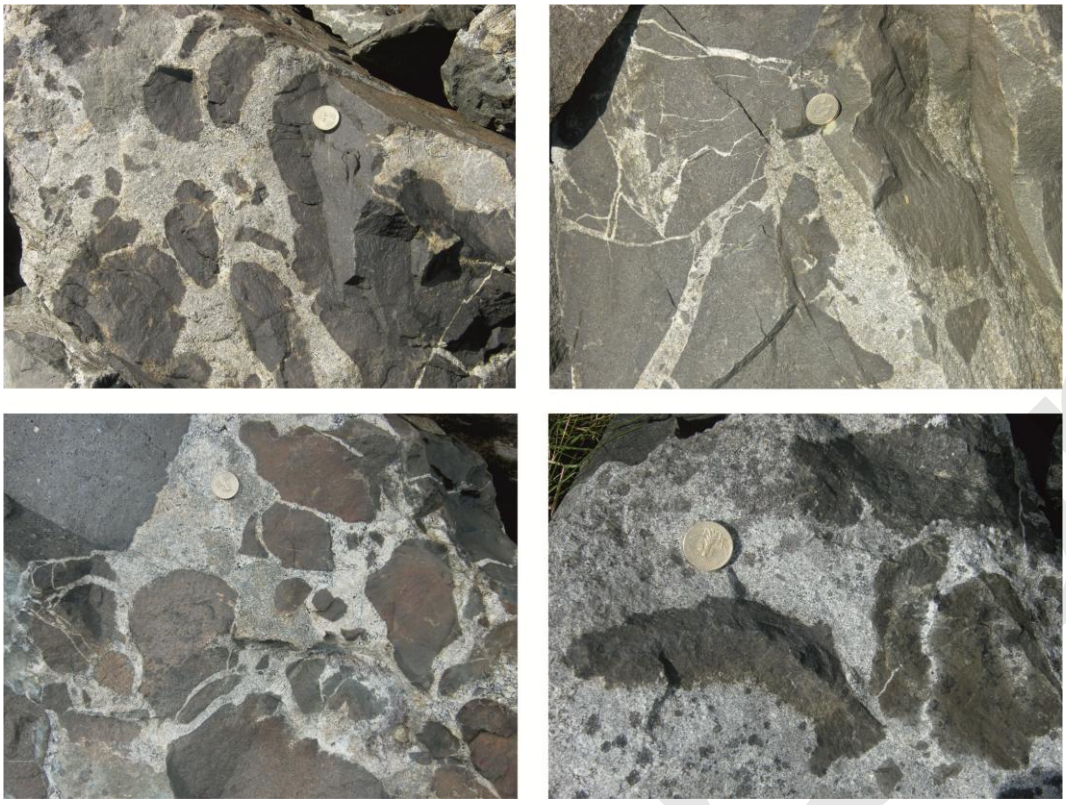


Figure 9-49: Examples of igneous breccias produced by the interaction of (pale) silicic and (dark) basic magmas, resulting in complex relationships ranging between angular fragments of basic rock (typically dolerite) veined by silicic rock (typically microgranite), and pillows of basic rock within silicic rock. Coin *ca.* 24 mm across. [Photographs courtesy of David Brown]

The Conachair Granite is the youngest major intrusion on Hirta (Figure 9-50; Figure 9-51; Figure 9-52). It forms the peninsula containing the hills of Conachair and Oiseval. The granite is a somewhat drusy, leucocratic, medium-grained rock, and its exposures have a distinctive slabby appearance caused by prominent horizontal and vertical joints. The rock consists largely of intergrown quartz and microperthitic alkali feldspar and albite, with small amounts of calcic amphibole and biotite. Chevkinite, titanite and zircon are accessory minerals. The granite is in sharp, but not noticeably chilled contact with the Mullach Sgar Intrusion-complex and with the gabbro and dolerite breccias, both of which are altered near the contacts.



Figure 9-50: Oisebhail, on the NE side of Loch Hiort, composed of poorly exposed Conachair Granite.

Beta version



Figure 9-51: Conachair (left) and Oisebhail (right), on the north side of Loch Hiort, composed of the Conachair Granite.



Figure 9-52: Conachair, in north Hirta, composed of the Conachair Granite.

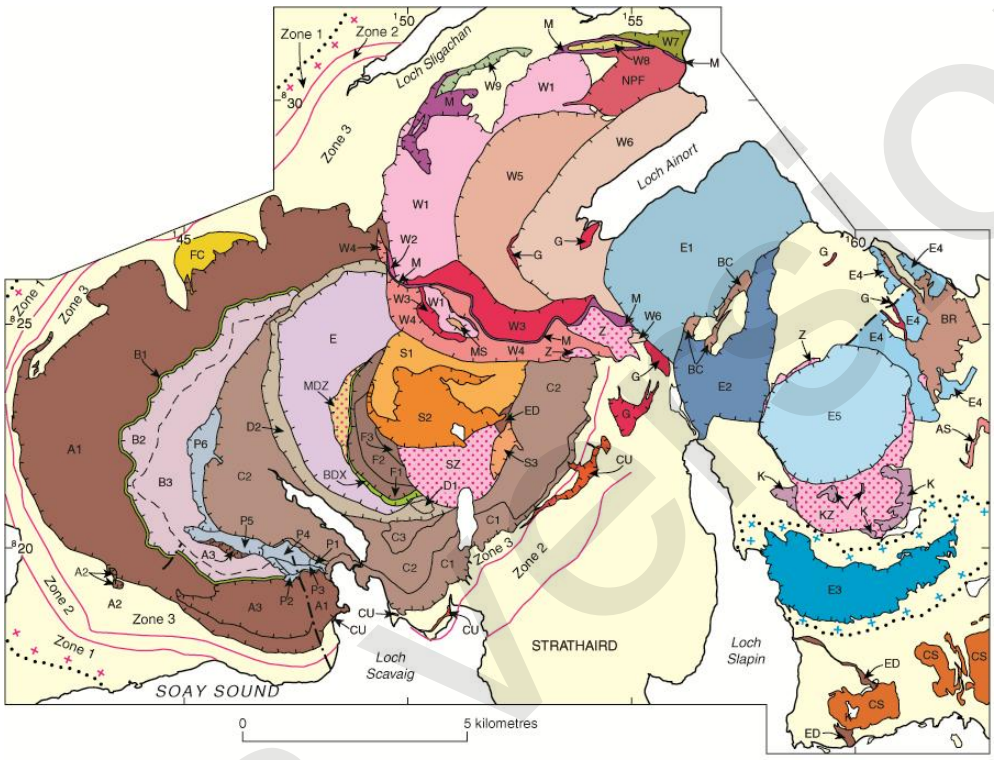
Numerous sheets and dykes of basic and silicic composition, and composite (basic-silicic) sheets cut all of the central complex lithologies, being most conspicuous in the pale-weathering cliffs formed of Conachair Granite. The dykes and inclined sheets appear to converge on a common focus at depth, east of Hirta.

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9.7 Skye Central Complex

9.7.1 Introduction

The Skye Central Complex comprises the Cuillin (oldest), Srath na Crèitheach, Western Red Hills and Eastern Red Hills (youngest) intrusive centres (Figure 9-1; Figure 9-53; Figure 9-54; Figure 9-55) (Bell & Williamson 2024).



EASTERN RED HILLS CENTRE

- E5 **Beinn na Caillich Granite:** granophyric-textured, relatively coarse-grained, macroporphyritic with alkali feldspar and quartz phenocrysts, hornblende- and biotite-bearing. Miarolitic, with quartz, alkali feldspar and fluorite. Chilled marginal facies locally, with microphenocrysts of ferrohedenbergite and fayalite
- E4 **Creag Strollamus Granites:** granophyric-textured, variably coarse- to medium-grained, macroporphyritic with alkali feldspar and quartz phenocrysts, amphibole- and biotite-bearing
- E3 **Beinn an Dubhaich Granite:** granophyric-textured, relatively coarse-grained, macroporphyritic with alkali feldspar and quartz phenocrysts, amphibole- and biotite-bearing. Rare rounded basaltic inclusions. Alkali pyroxene-bearing facies in vicinity of skarns at margin
- E2 **Beinn na Cro Granite:** porphyritic with phenocrysts of alkali feldspar and quartz, amphibole- and biotite-bearing
- E1 **Glas Bheinn Mhor Granite:** granophyric-textured, macroporphyritic with plagioclase phenocrysts, amphibole- and biotite-bearing. Rare rounded basaltic inclusions

Other intrusions and volcaniclastic deposits associated with the Eastern Red Hills Centre

- BR **Broadford Gabbro:** variably medium- to coarse-grained, unlayered, typically hydrothermally altered
- BC **Beinn na Cro Gabbro:** variably medium- to coarse-grained, unlayered, typically hydrothermally altered. Composed of sheet-like masses
- K **Kilchrist Hybrids:** leucocratic to mesocratic, medium-grained rocks. Contain irregular crystals of quartz fringed by amphibole and/or pyroxene and resorbed crystals of alkali feldspar. Common rounded basaltic inclusions. Flow banding common in marginal facies
- KZ **Kilchrist Breccias:** predominantly unbedded coarse breccia with clasts of basalt, hawaiite, quartzite, Torridonian sandstone and fissile mudstone, Ordovician dolostone, Jurassic limestone, sandstone and siltstone. Matrix of hydrothermally altered volcaniclastic siltstone and finely comminuted fragments of clast lithologies

WESTERN RED HILLS CENTRE

- W9 **Eas Mor Granite:** microgranite with phenocrysts of microperthite, amphibole-bearing
- W8 **Meall Buidhe Granite:** microgranite with phenocrysts of plagioclase; fayalite- and ferrohedenbergite-bearing
- W7 **Maol na Gainmhich Granite:** relatively coarse-grained, arfvedsonite-bearing
- W6 **Loch Ainort Granite:** granophyric-textured, glomeroporphyritic with anorthoclase phenocrysts; ferrohedenbergite-, fayalite- and amphibole-bearing, pegmatitic in parts
- W5 **Beinn Dearg Mhor Granite:** granophyric-textured, glomeroporphyritic with anorthoclase phenocrysts; ferrohedenbergite-, fayalite- and amphibole-bearing
- W4 **Marsco Granite:** granophyric-textured, relatively coarse-grained, miarolitic in part, fluxioned in part, ferrohedenbergite- and fayalite-bearing
- W3 **Southern Porphyritic Granite:** granophyric-textured, macroporphyritic with alkali feldspar and quartz phenocrysts, brecciated in part
- W2 **Glen Sligachan Granite:** macroporphyritic with plagioclase and alkali feldspar phenocrysts, minor ferrohedenbergite, fayalite, amphibole and biotite
- W1 **Glamaig Granite:** amphibole- and biotite-bearing, with abundant rounded basaltic inclusions
- NPF **Northern Porphyritic Felsite:** granophyric-textured, macroporphyritic with alkali feldspar and quartz phenocrysts, ferrohedenbergite- bearing in part. Abundant rounded basaltic inclusions. Flow-banded and brecciated in part
- M **Marsco Hybrids:** a composite ring intrusion of *'marscoite'* (a hybridised, medium-grained, intermediate rock with xenocrysts of quartz, alkali feldspar and plagioclase), *ferrodiorite* (with or without phenocrysts of plagioclase), *'glamaigite'* (a heterogeneous, hybridised, coarse-grained intermediate rock) and *porphyritic felsite* (granophyric-textured with phenocrysts of alkali feldspar and quartz)
- MS **Marsco Summit Gabbro:** unlayered, olivine-poor, brecciated in part

Figure 9-53: Simplified geological map of the Skye Central Complex (after Emeleus & Bell 2005).

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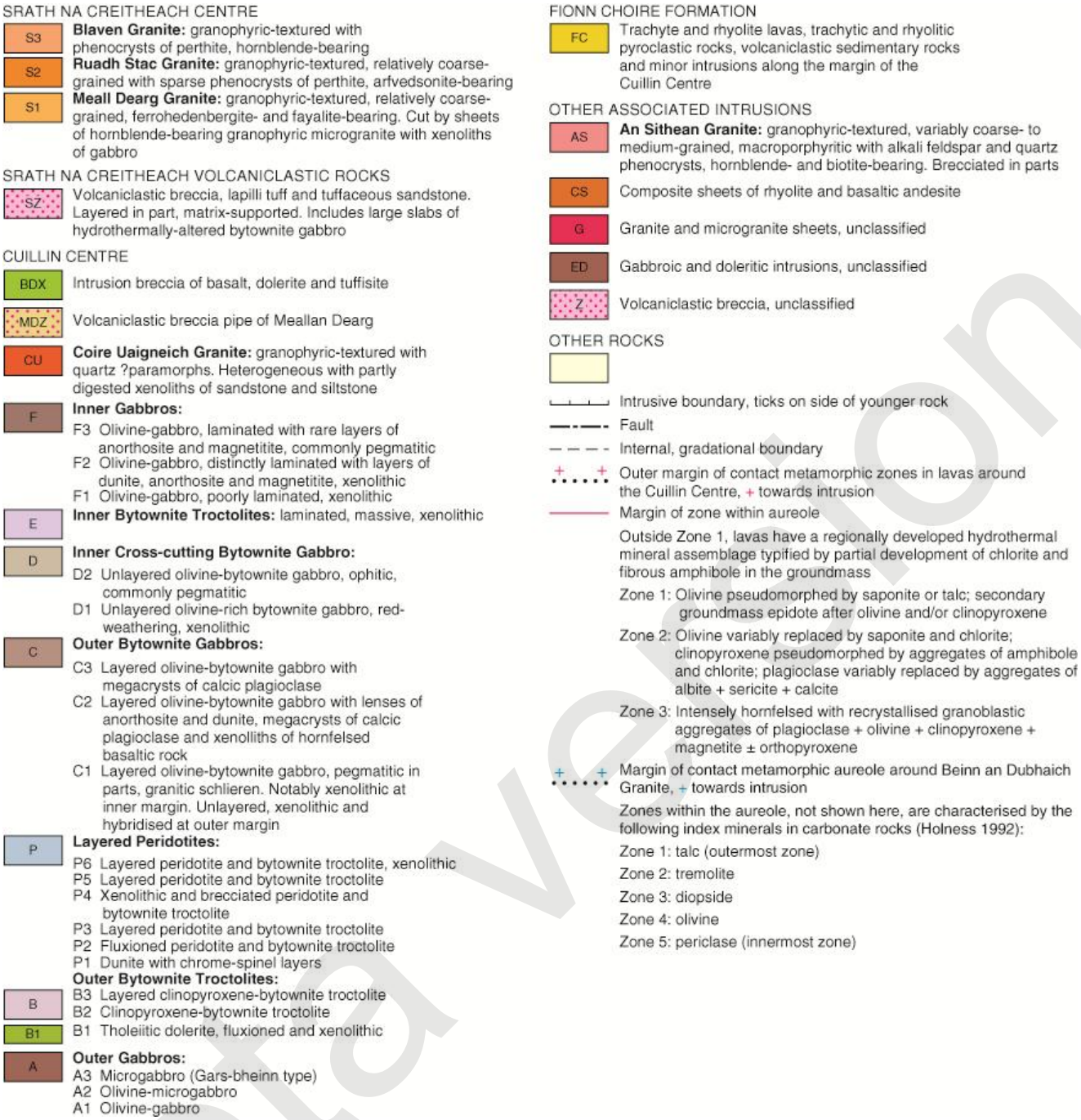


Figure 9.53: Simplified geological map of the Skye Central Complex [continued] (after Emeleus & Bell 2005).

The Cuillin Intrusive Centre (CIC) consists of peridotite, troctolite and gabbro ring-intrusions, some of which have well-developed mineral layering and lamination.

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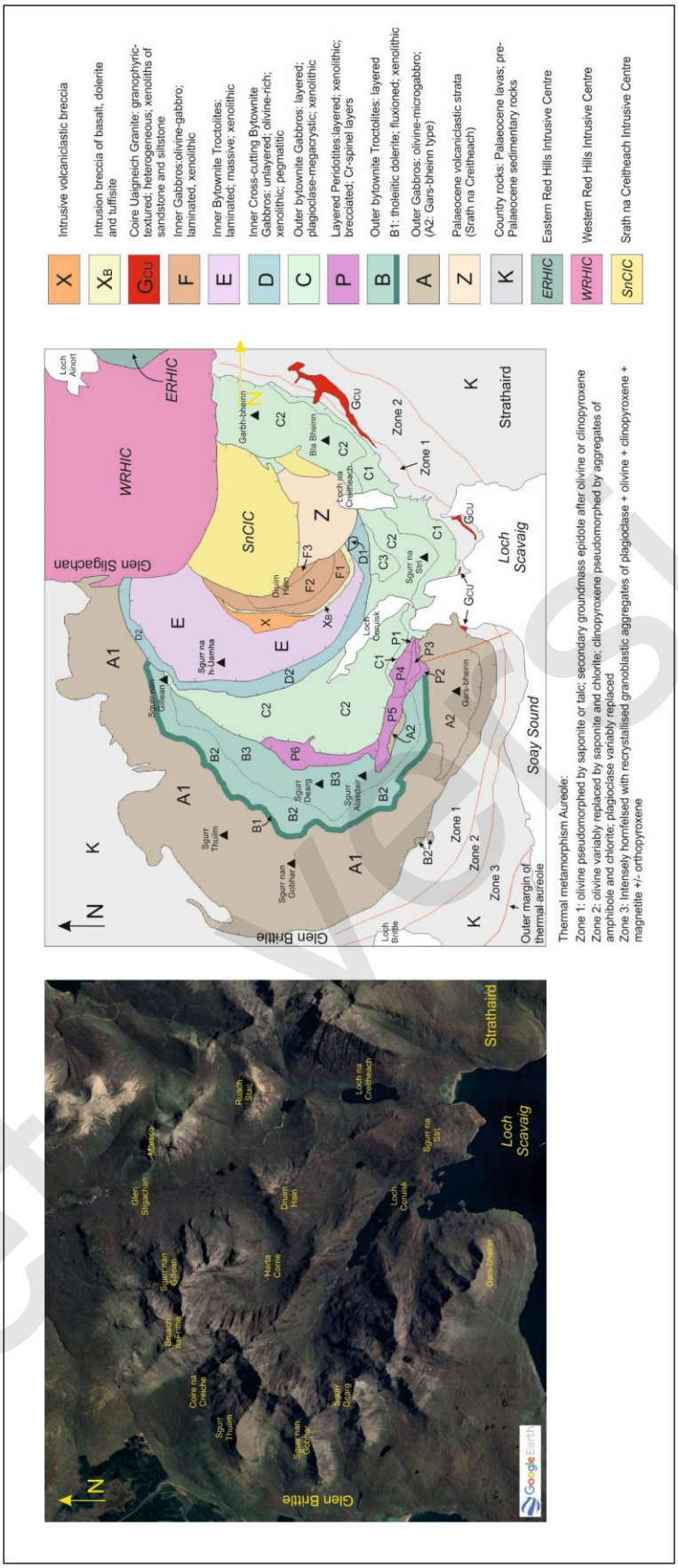


Figure 9-54: Lithodemic units of the Cuillin Intrusive Centre (CIC) (after BGS 2005 and Emeleus & Bell 2005) and Google Earth© image of the same area.

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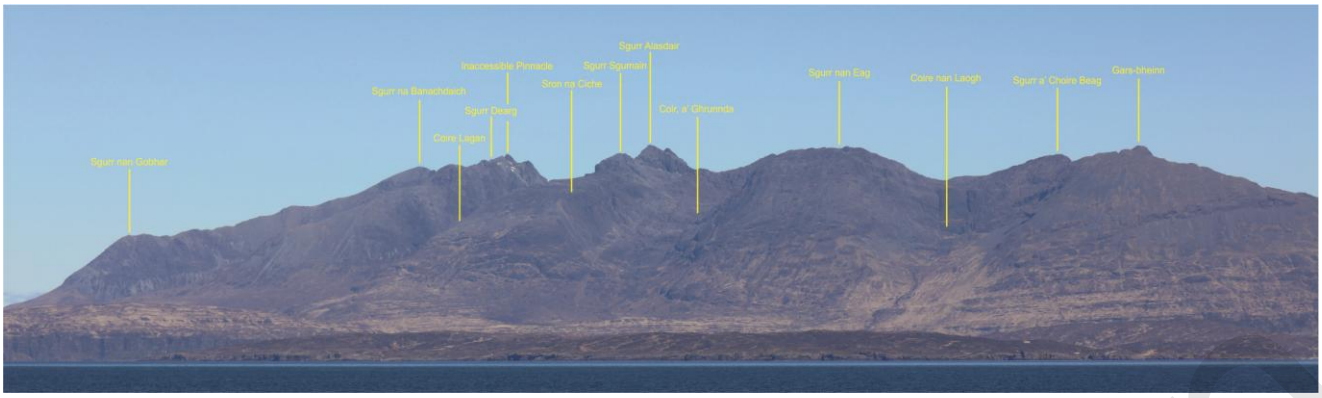


Figure 9-55: The main arc of the Cuillin, viewed towards the NE from Sanday.

These structures attracted the attention of early geologists, who attributed the layering in the gabbros of Druim Hain to intrusion of a heterogeneous magma (Harker 1904). These coarse-grained rocks are cut by numerous centrally inclined, fine-grained sheets of tholeiitic basalt and dolerite, and are also invaded by volcaniclastic breccia pipes. All the units of the intrusive centre are cut by NW-SE -trending basaltic dykes of the Skye Regional Dyke Swarm (Chapter 7). The margin of the intrusive centre is steeply inclined inwards, as are many of the well exposed internal contacts between various basic and ultrabasic intrusions, resulting in an overall nested disposition. In general terms, the intrusions are oldest around the margin of the intrusive centre, younging progressively inwards. The NE quadrant of the intrusive centre is absent because of the emplacement of the younger granites of the Srath na Creithèach and Western Red Hills granite intrusive centres (see below).

Geographically, the complex has two distinct parts. The most prominent is that forming the main Cuillin ridge, running from Sgùrr nan Gillean in the north, to Gars-bheinn in the south, an arc which is concave to the east. The numerous peaks that constitute the main ridge are all just under 1000 m OD and give rise to a very irregular alpine topography, mainly due to Quaternary glaciations (Chapter 13) and the subsequent inweathering and outweathering of minor intrusions, cone-sheets and dykes, that cut the various gabbros, troctolites and peridotites. On the convex side of the ridge, several corries are separated by buttress-like ridges, for example Coire Làgan and Coir’ a’ Ghrunnda separated by Sròn na Cìche. Two large drainage areas have developed within the amphitheatre east of the ridge: Harta Corrie in the north and Coir'-uisg in the south. These two areas are separated by the ridge of Druim nan Ramh, which lies to the north of Loch Coruisk (Figure 9-56); Figure 9-57).

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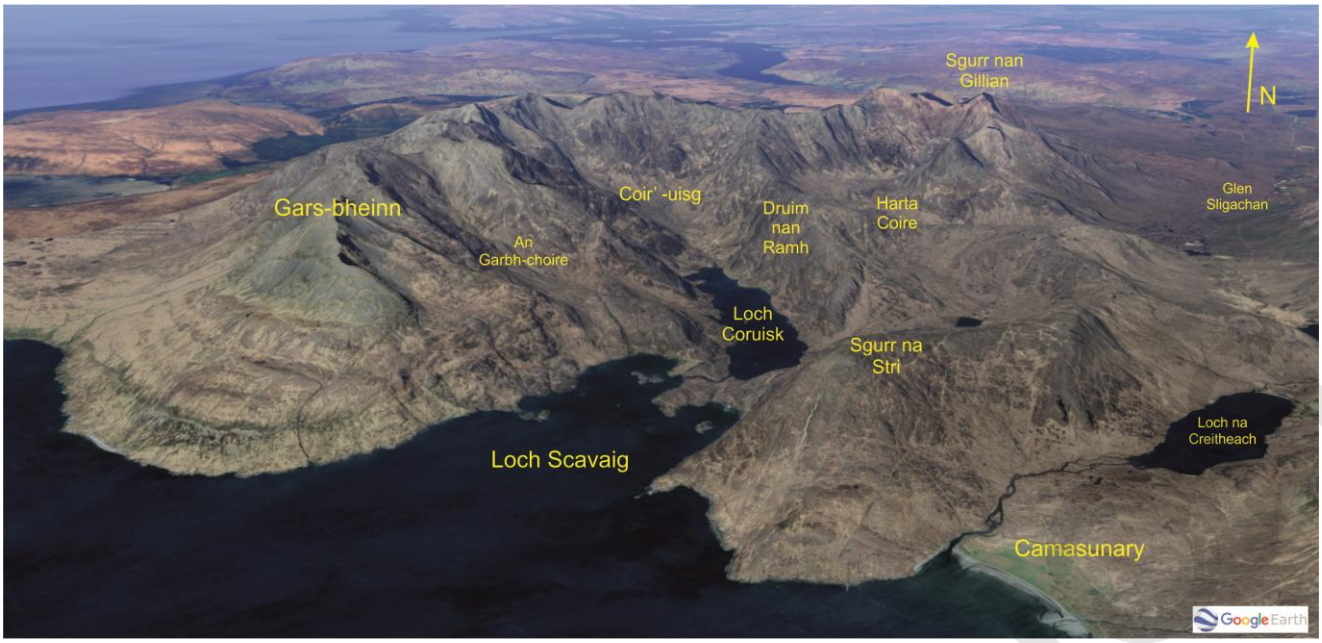


Figure 9-56: Oblique Google Earth© image indicating some topographic features of the Cuillin, Skye.



Figure 9-57: Coir' a' Ghrunnda, southern Cuillin, composed of pale weathering bytownite troctolites, exposed on large 'boiler plates' with near 100% exposure as a result of Quaternary glaciation. In the distance are the summits of Sgùrr Sgumain and Sgùrr Alasdair. View from Soay

The isolated, eastern part of the CIC forms the Garbh-bheinn - Blà-bheinn (Blaven) ridge, which lies to the east of Loch na Crèitheach. The main rock-units that have been identified within the Cuillin (*s.s.*) can be traced into this eastern sector.

9.7.2 Country-rock alteration

The emplacement of large volumes of basic and ultrabasic magma into the crust produced several changes in both the early-formed units of the CIC (Ferry 1985a) and in the surrounding country-rocks (Ferry *et al.* 1987). Alteration was caused by a combination of the large amount of heat liberated by the crystallising magmas, and by the circulation of heated meteoric fluids (groundwater), mainly supercritical H_2O (Forester & Taylor 1977).

As the various peridotites, troctolites and gabbros crystallised, hydrous fluids were able to gain access, along crystal boundaries and, on a larger scale, along fractures that formed in response to volume reduction and stress release during cooling. Most of the fracture networks that formed were subsequently sealed by the precipitation of hydrothermal minerals, commonly in complex assemblages, to form quasi-planar veins (Figure 9-58).

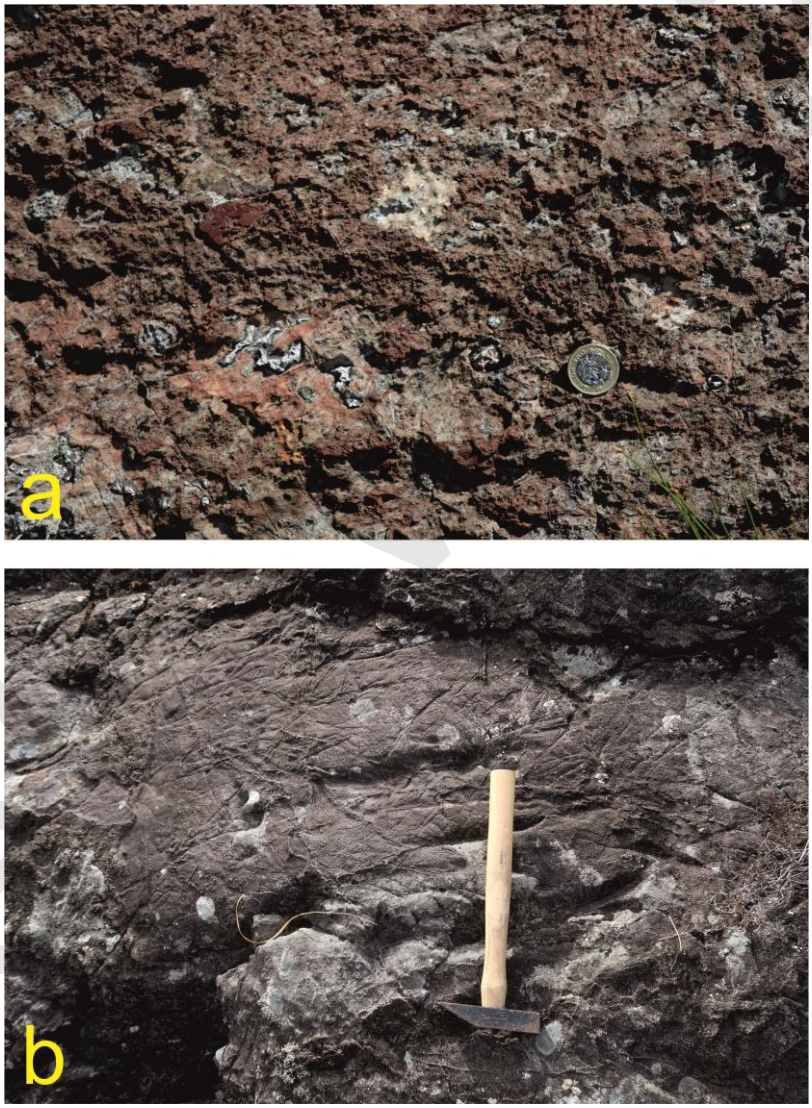


Figure 9-58: Intensely altered/hornfelsed amygdaloidal basaltic lava (pyroxene hornfels, within the Inner Zone of Almond (1964), see below): (a) south of Gars-bheinn, adjacent to unnamed lochans, coin *ca.* 24 mm across; and, (b) on the west side of the Abhainn Camas Fhionnairigh, immediately SE of the margin of the CIC, hammer *ca.* 30 cm long.

Primary (magmatic) minerals locally underwent reaction with these fluids to form secondary talc, chlorite, montmorillonite, amphibole, biotite and magnetite. Less common was the formation of calcite, epidote,

quartz, titanite, prehnite and garnet. The alteration process led to minor changes in the bulk composition of the original rocks, with the addition of relatively mobile elements such as K and Na, and a loss of Mg. Most of the mineralogical alteration occurred within the temperature range *ca*. 450-550°C, with the most resistant mineral to alteration being clinopyroxene. However, stable isotope data (oxygen and hydrogen), for surviving magmatic minerals, indicate that fluid-mineral reaction occurred at higher temperatures, from *ca*. 1000°C (i.e. just below the temperature that the basic and ultrabasic magmas had fully crystallised), down to *ca*. 500°C. During this high-temperature period of fluid-mineral reaction, oxygen and hydrogen in the fluid equilibrated with oxygen and hydrogen in the minerals but did not result in the formation of secondary hydrous minerals, which are not stable at such high temperatures, enabling the anhydrous magmatic minerals to survive, apparently unaltered (Forester & Taylor 1977; Ferry 1985a).

Investigations into the nature of the (country-rock) Torridonian sedimentary rocks in Camasunary Bay by Almond (Almond 1960, 1964) and Jassim (1970) provide evidence of the significant amount of heat transferred from the Cuillin Intrusive Centre (CIC) into the country-rocks. Along the exposures on the east side of Camasunary Bay, 'normal' Torridonian strata are encountered, predominantly medium- to coarse-grained, bedded sandstones and siltstones of the Blà-bheinn Member (Chapter 2), intruded by dolerite and basalt (cone)-sheets.

In a traverse to the NW, towards the margin of the CIC, a number of significant changes to the character of these rocks has taken place (Figure 9-59; Figure 9-60; Figure 9-61; Figure 9-62; Figure 9-63). Initially, the rocks take on a slightly bleached appearance and in thin-section there is evidence that some recrystallisation has taken place. Within 100 m of the margin of the CIC, rheomorphism (mobilisation) of material within the Torridonian strata has taken place, resulting in pale, cross-cutting, rhyolitic/micro-granitic veins. This material is, in many ways, like that of a nearby silicic intrusion, the Coire Uaigneich Granite (see below). These veins cut less-altered Torridonian strata and various dolerite and basalt minor intrusions. Some of the minor intrusions show evidence of distortion in the form of sinuous contacts at their margins, which may reflect the non-brittle nature of the country-rock during their emplacement.

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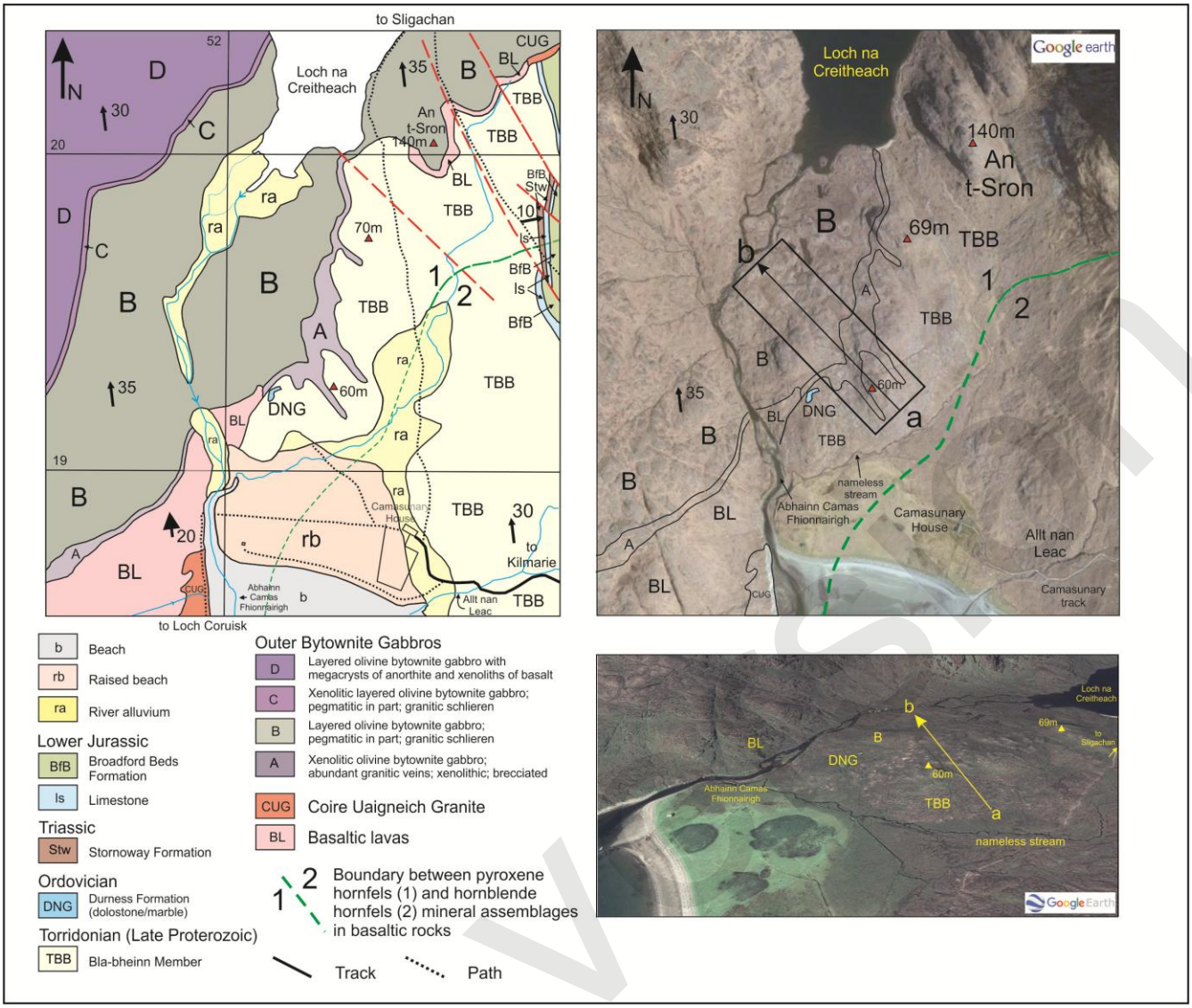


Figure 9-59: Location of traverse in Camasunary Bay, where Torridonian strata (Blà Bheinn Member, see Chapter 2) are the dominant country-rocks, displaying increasing degrees of modification towards the margin of the Cuillin Intrusive Centre.

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Figure 9-60: Relatively unmodified Torridonian strata of the Blà Bheinn Member close to where the main Camasunary track crosses the Abhainn nan Leac. Ruler 30 cm long.



Figure 9-61: Torridonian strata of the Blà Bheinn Member cut by basaltic dykes with irregular margins. Locally, the sedimentary material has deformed due to intense heating by the nearby CIC. Note boudinaged character of the intrusion in the centre of the image. Pole *ca.* 1 m long. long.



Figure 9-62: Brecciated and intensely veined Torridonian strata of the Blà Bheinn Member close to the margin of the CIC. The veins are composed of microgranite. Pole *ca*. 1 m long.



Figure 9-63: Relatively homogeneous, unlayered Outer Bytownite Gabbros cut by microgranite veins close to the margin of the CIC on a large, glacially-sculpted slab on the east side of the Abhainn Camas Fhionnairigh. Pole *ca*. 1 m long.

Preliminary version

As the irregular ‘boundary zone’ of the Outer Bytownite Gabbros (see below) with the country-rock Torridonian strata is crossed, the intensity and complexity of the cross-cutting rhyolitic/micro-granitic veins increases, and they are a common feature within the marginal gabbros of the CIC as far west as the Abhainn Camas Fhionnairigh.

Within Camasunary Bay there is a small outcrop of marble, originally attributed a Jurassic age (Peach *et al*. 1910) (Figure 9-64). In a mineralogical study of this rock, Wyatt (1952) identified two high-temperature calc-silicate minerals, spurrite and rankinite. A subsequent assessment by Beard & Drake (2007), identified melilite, another high-temperature calc-silicate mineral, together with wollastonite, vesuvianite, tilleyite, andradite-grossular garnet, monticellite and perovskite, all indicative of extremely high-grade thermal metamorphism, within the Sanidinite Facies and with a peak metamorphic temperature possibly in excess of 900°C at an assumed depth of no more than 1 km. Metamorphism was not isochemical and the rock is better described as a skarn. The identification of chert nodules and stringers, similar to those in Cambro-Ordovician Durness Group dolostones within the Moine Thrust Zone exposed to the east in the district of Strath and on Sleat (Chapter 2), together with the development of abundant calc-silicate minerals, is used by Beard & Drake (2007) to argue that the original rock was a dolostone with a more likely Cambro-Ordovician age. One inference of this interpretation is that the (not seen) contact between the metamorphosed dolostone and surrounding Torridonian strata (Chapter 2) is a thrust plane, with the latter structurally above the former, as is the case for the Kishorn Thrust Plane, which crops out NW of Bheinn Shurdail in Strath (Chapter 2).



Figure 9-64: Metamorphosed dolostone (marble) in Camasunary Bay, interpreted to be part of the Durness Group, with a complex assemblage of high-temperature (calc-silicate) minerals. Pole *ca*. 1 m long.

The thermal effects of the CIC are also recorded by the mineralogy of the adjacent plateau lavas south of Sgùrr na Stri, in Camasunary Bay and on Strathaird (Almond 1960, 1964). Hutchison (1964) described a

similarly high grade of contact metamorphism within the amygdaloidal basaltic lavas adjacent to the margin of the Cuillin Intrusive Centre in the Allt a' Choire Ghreadaidh on the east side of Glen Brittle.

Almond (1964) defined three zones within the thermal aureole along the SE margin of the CIC (Figure 9-65). The highest grade of thermal metamorphism is defined as a pyroxene hornfels, with four textural types of basalt recognised, ranging from lavas that retain their igneous mineral textures, through to lavas where recrystallisation is almost complete, containing a mineral assemblage of plagioclase, clinopyroxene, orthopyroxene and (metamorphic) olivine, typical of Sanidinite Facies thermal metamorphism, which persists out to a distance of at least 200 m from the contact. Temperatures were higher than 900°C, possibly as high as 1,000°C (Ferry *et al.* 1987). This gives way to basaltic lavas in the general range 200-1,000 m from the margin of the CIC and defined as being hornblende hornfels, a subdivision of the Albite-epidote Facies, containing actinolite, chlorite, albite and epidote. Still further out, for a distance of at least 5 km from the margin of the CIC, the lowest grade of metamorphism within the lavas along this sector of the country-rocks contains only chlorite, albite and epidote, and primary magmatic textures are reasonably well preserved. These relatively unaltered rocks have developed their secondary mineral assemblage largely due to burial and the circulation of heated meteoric/ground water due to the elevated temperatures caused by the various magmatic processes.

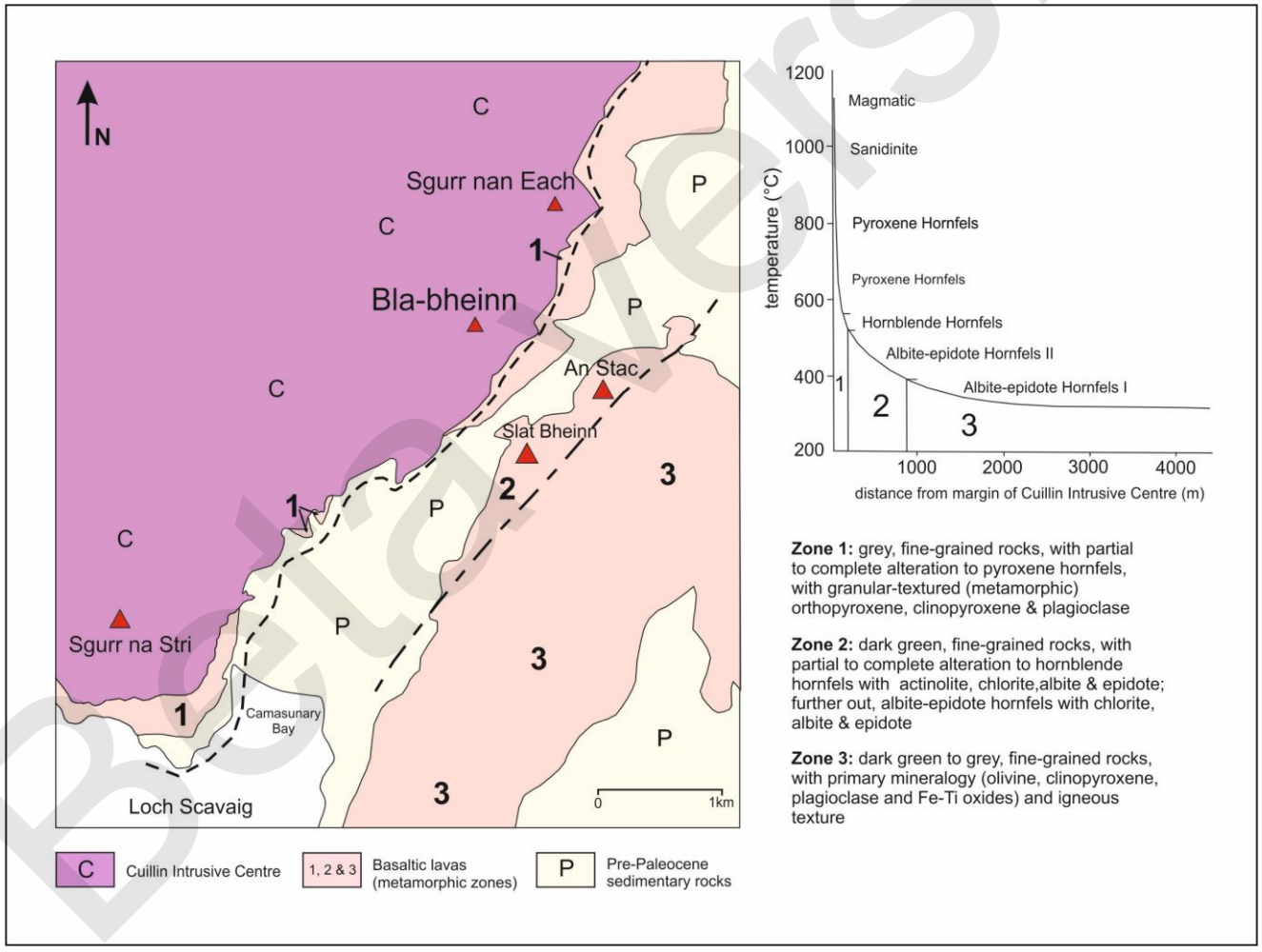


Figure 9-65: Zones of thermal alteration within the basaltic lavas on Strathaird and south of Sgùrr na Stri (after Almond 1964).

The thermal metamorphism of the lavas along the western margin of the CIC has been investigated by Ferry *et al.* (1987) (Figure 9-66). The highest grade is within their Orthopyroxene-olivine Zone (>900°C),

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defined by metamorphic olivine, orthopyroxene and biotite. The adjacent lavas are within the Amphibole Zone (400-900°C) and contain the amphiboles actinolite and edenite, together with chlorite, titanite, epidote, andradite and quartz. Further out are rocks in the Smectite Zone (<400°C), containing saponite and carbonate, but lacking primary (i.e. magmatic) olivine and containing considerably less zeolites than in the Primary Olivine Zone, which comprises basaltic lavas dominated by magmatic minerals with original igneous textures. The extent of thermal metamorphism is strongly coupled to the degree of reaction and exchange between the rocks and circulating meteoric fluids, as deduced from their whole-rock $\delta^{18}O$ signatures. Furthermore, the anhydrous character of the Orthopyroxene-olivine Zone rocks indicates that any significant rock-fluid reaction did not occur after temperatures dropped below *ca*. 900°C. To a significant extent, the metamorphic process was isochemical and the whole-rock compositions of the lavas have not been substantially modified (Ferry *et al*. 1987).

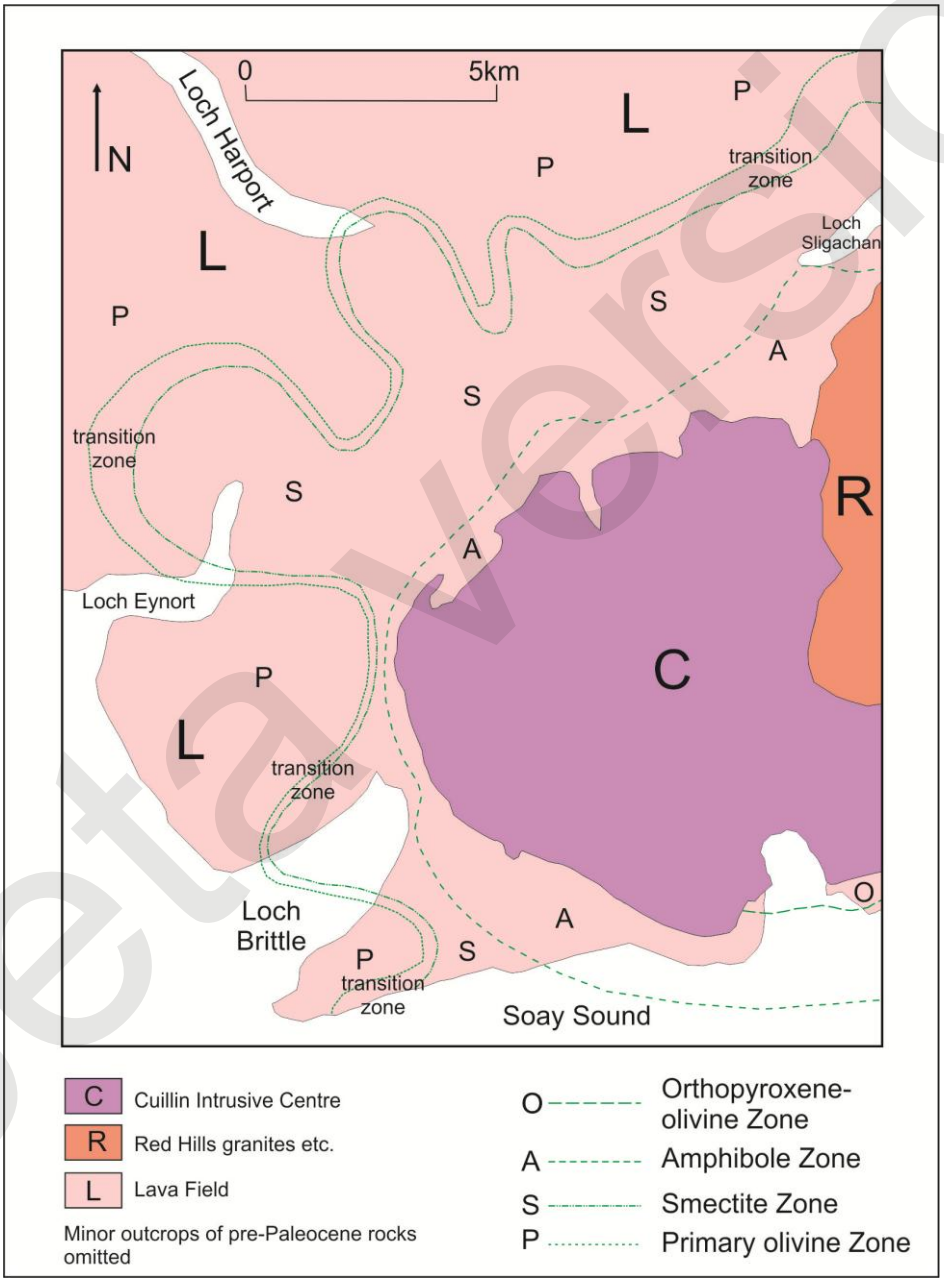


Figure 9-66: Zones of thermal alteration in the basaltic lavas adjacent to the western margin of the CIC (after Ferry *et al*. 1987).

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9.7.3 Details of the main units

The constituent units of the Cuillin Intrusive Centre (CIC) are shown on Figure 9-53 and Figure 9-54 and are described below in order of intrusion.

9.7.3.1 The Outer Gabbros (A)

This ring-shaped, heterogeneous, coarse-grained unit forms a distinct marginal part of the CIC on the western, convex side of the main Cuillin Ridge. The outer contact, against country-rock basaltic lavas, is only locally exposed, typically where cut by a water course, for example in the Allt a' Choire Ghreadaidh on the east side of Glen Brittle. Well-developed layering (*s.s.* layers) is generally absent, and these rocks are believed to constitute some of the earliest material of the CIC.

Weedon (1961), Hutchison (1964) and Hutchison & Bevan (1977) identified two distinct rock-units within the Outer Gabbros in the southern part of the CIC, in the area between Coir' a' Ghrunnda and Loch Scavaig, including the summit area of Gars-bheinn. These are (Figure 9-67): (a) an Outer Marginal Gabbro (A1); and, (b) a micro-gabbro (A2), the Gars-bheinn Gabbro (and its altered variant, the 'Gabbro with Clouded Feldspars' of Weedon (1961).

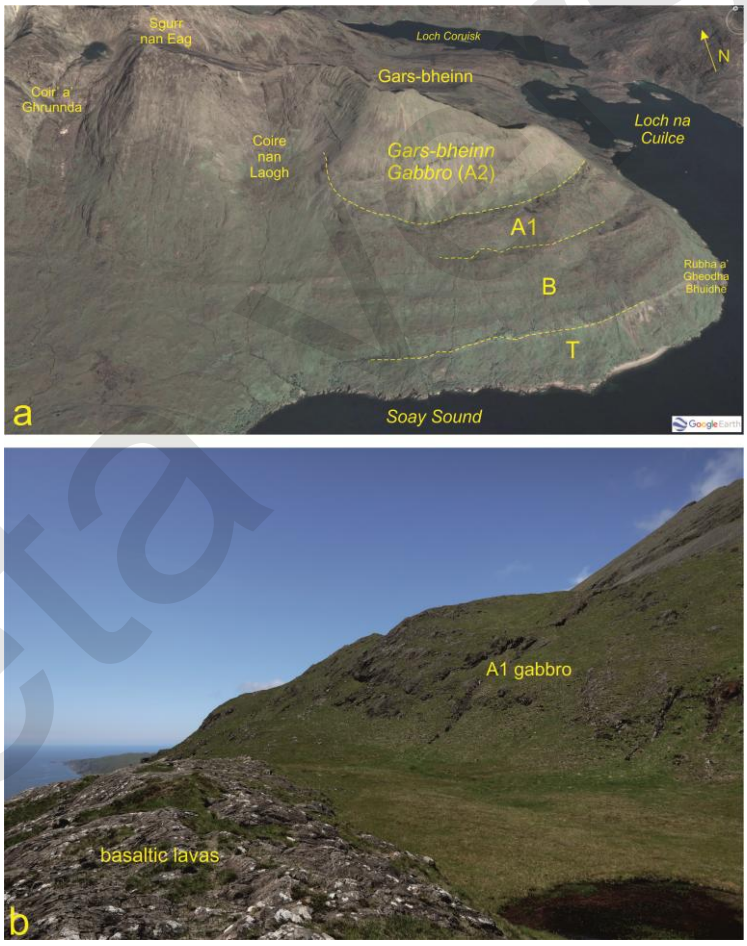


Figure 9-67: (a) Oblique Google Earth© image towards the NE of the southern part of the Cuillin, indicating the approximate outcrop of the A1 and A2 gabbros on Gars-bheinn, together with hornfelsed basaltic lavas (B) unconformably overlying Torridonian strata (T); and, (b) field view towards the west along intrusive contact between the A1 gabbro and country-rock hornfelsed basaltic lavas.

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Rare xenoliths of peridotite within the altered variant of A2 (i.e. with altered plagioclase crystals or ‘clouded feldspars’) north of the Allt Coir' a' Chruidh indicated to Hutchison & Bevan (1977) and Bevan & Hutchison (1984) that the A2 gabbro post-dates at least some peridotite intrusion(s).

The following descriptions are mainly from Weedon (1961).

The A1 Outer Gabbros have an inward-dipping outer contact with the country-rock lavas that is > 40°, although it is not typically exposed along much of its outcrop and may (at the present level of erosion) dip, locally, inwards and outwards. These gabbros are relatively variable in character, typically unlayered with localised (gabbro) pegmatites, and comprise complex-zoned crystals of calcic plagioclase (up to An_{80}), magnesian olivine and relatively unaltered clinopyroxene.

The A2 Gabbro (Gars-bheinn Gabbro) crops out on the summit of that name (Figure 9-67), as well as on Sgùrr a' Choire Bhig, where it may be identified as a slightly altered, fine-grained, smooth-weathering gabbro. It has a green coloration, particularly in the vicinity of darker, fine-grained, basic sheets that are present within the intrusion (see below). Where exposed, A2 has a sharp contact with A1 and ‘B’ gabbros/troctolites (Figure 9-68 and see below). Petrographically, the unaltered A2 gabbro is composed of plagioclase ($An_{65–68}$, but with cores as calcic as An_{74}), and clinopyroxene, in an ophitic textural arrangement. Interstitial patches are present: either glass, or sodic plagioclase, or alkali feldspar. The glassy material may possibly represent an extreme fractionate, with a composition close to that of granite. Northwards, the A2 gabbro grades into its altered variant (the Gabbro with Clouded Feldspars of Weedon (1961); see below). The upper contact, to the south, with the A1 Outer Gabbros, however, is sharp, being marked by a distinct topographic depression.

The altered A2 gabbro (Gabbro with Clouded Feldspars) is very similar to the unaltered A2 gabbro but is distinguished from it by the alteration present within the plagioclase crystals, and in some pyroxenes. It is exposed in the area NE of Sgùrr nan Eag and Sgùrr a' Choire Bhig. The boundary between the unaltered and altered gabbros is not sharp. Weedon (1961) suggested that these differences may be due solely to the ingress of (hydrothermal) fluids at elevated temperatures, which were enriched in iron. The subsequent emplacement of the Layered Peridotites to the north (see below) may be important in this respect, being a potential source of heat to drive convective hydrothermal systems.

9.7.3.2 The Border Group (B1 and B2)

The presence of a Border Group of rocks (B1 in Figure 9-68) to the ‘B’ group of rocks was first proposed by Zinovieff (1958) and investigated in detail by Hutchison (1964, 1968). Its contact with the Outer Gabbros (see above) is exposed in Coire Làgan on the buttresses on the south side of the corrie. The material at the outer margin of the Border Group is a tholeiitic basalt containing xenoliths of bytownite gabbro. Progressing away from the contact to the east, the Border Group grades into a ‘zone of wispy banding' (Hutchison 1968) which, in general, persists for *ca*. 30 m, before grading into unlayered bytownite troctolites (B2 in Figure 9-70): the 'White Allivalite' of Hutchison (1968) and layered bytownite troctolites (B3 in Figure 9-68). The zone of wispy banding dips steeply inwards (eastwards), at an average angle of *ca*. 80°, and forms a boundary layer that can be traced intermittently for over 5 km along strike, to the north and south (Hutchison 1968). Some of the most spectacular exposures of these B2 bytownite troctolites form the expansive slab-like ‘boiler plates’ in Coir’ a’ Ghrunnda (Figure 9-67; Figure 9-68; Figure 9-69).

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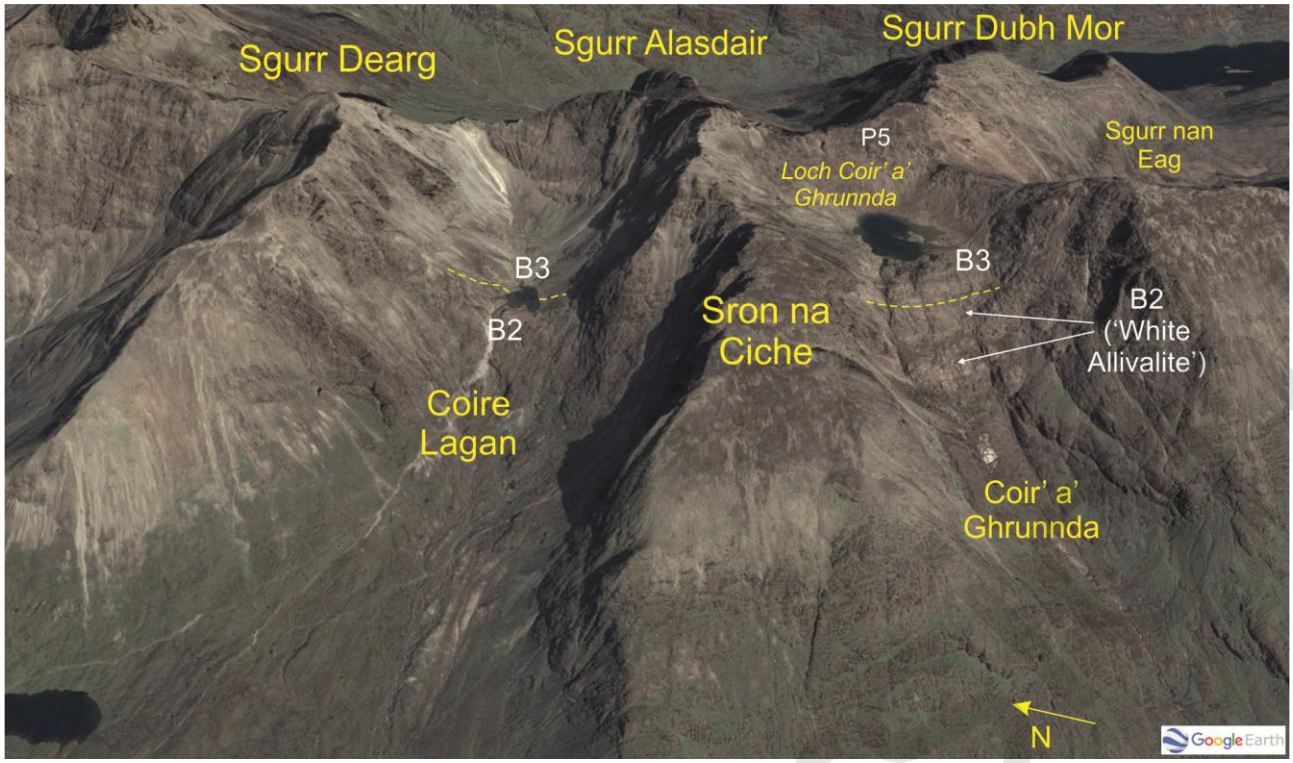


Figure 9-68: Oblique Google Earth© image of the SW part of the Cuillin, indicating the approximate outcrops of: B2 (Outer Unlayered Bytownite Troctolites or 'White Allivalite'); B3 (the Outer Layered Bytownite Troctolites); and, P5 (Layered Peridotites and Bytownite Troctolites) View towards the NE.

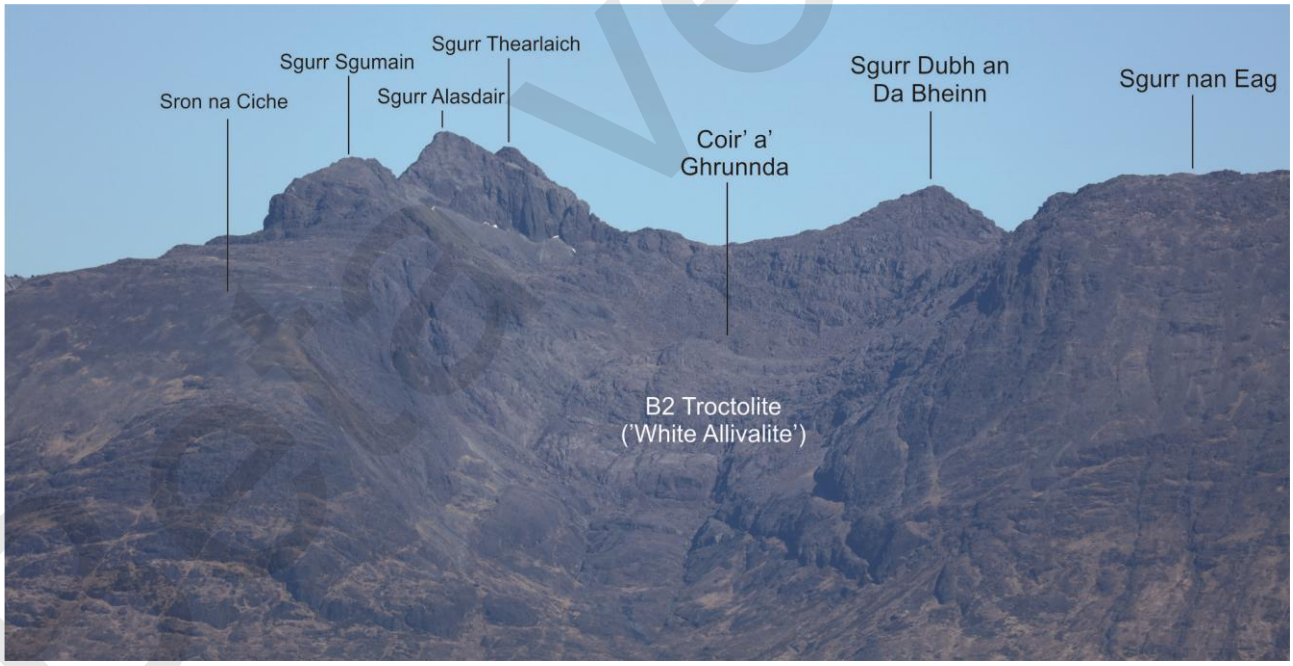


Figure 9-69: Coir' a' Ghrunnda, SW Cuillin, viewed towards NE from Sanday.



Figure 9-70: Outer Unlayered Bytownite Troctolites (B2) (the 'White Allivalite') forming a glacially sculpted 'boiler plate' in Coir' a' Ghrunnda, intruded by anastomosing basaltic minor intrusions.

The tholeiitic basalt at the margin of the Border Group contains olivine, two pyroxenes and intensely clouded plagioclases, with compositions of *ca.* An_{57} (Hutchison 1968). Progressing inwards (i.e. to the east) from the outer margin of the Border Group, the clouding within the plagioclase crystals diminishes and their compositions are more calcic (An_{85}). Textural variations are present within the 'zone of wispy banding', depending upon the inter-relationships of the pyroxenes and plagioclases. Crystal alignment textures are commonest near to the outer margin and die out inwards as the rock passes into coarse-grained, unlayered bytownite troctolite (B2).

The unlayered bytownite troctolite (B2; the 'White Allivalite') varies in width/thickness from *ca*. 200 m on the west side of Sgùrr Dearg, to *ca*. 600 m on the SW side of Sgùrr a' Mhadaidh. The incoming of (cumulus) olivine constitutes a demarcation between the unlayered bytownite troctolites (B2) and the subsequent rock unit, the layered bytownite troctolites (B3) (see below). The inner contact of the unlayered bytownite troctolites (B2) dips inwards (to the east) at an angle of approximately 60°, but as its outer contact dips inwards at a steeper angle, this distinctive unit must thin upwards and outwards.

The unlayered bytownite troctolites are coarse-grained, locally pegmatitic rocks rich in plagioclase intergrown with clinopyroxene. Cores of individual plagioclases tend to be euhedral, suggesting that at the time of emplacement, the magma had cooled below its liquidus temperature and contained a significant amount of plagioclase crystals. Hutchison & Bevan (1977) present evidence that the magma involved was picritic, rather than basic, as suggested by Wager & Brown (1968).

Hutchison (1968) envisaged the following steps in the development of the Border Group and the associated unlayered and layered bytownite troctolites within a funnel-shaped composite intrusion, requiring uplift of an (undefined) central block to create space for the incoming magma(s): (a) intrusion of a relatively thin sheet of tholeiitic basalt magma, with a cone-like geometry, possibly with entrained

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xenoliths, into intensely fractured Outer Gabbro(s), which cools and crystallises calcic plagioclases with random orientations; (b) further intermittent injections of similar magma and associated uplift to produce the rocks within the 'zone of wispy banding' - localised more-hydrous magma produced the randomly-distributed pegmatites; (c) further major uplift, interior to these marginal lithologies, associated with voluminous injection(s) of similar plagioclase-bearing basaltic magma, to produce the unlayered bytownite troctolites during periods of static crystallisation, and layered bytownite troctolites, with plagioclase-pyroxene and plagioclase-olivine cumulates, during periods when convective overturn and crystal accumulation took place, the latter banking up against the inner margin of the former.

9.7.3.3 The Outer Layered Bytownite Troctolites (B3)

The Outer Layered Bytownite Troctolites (B3) have an estimated thickness of 1,800 m and have been subdivided into five units (Zinovieff 1958) (Figure 9-54; Figure 9-71). Except for the lowest unit (Unit 1), the basis of the divisions is plagioclase-pyroxene cumulates grading upwards into plagioclase-olivine cumulates, with the latter having good, small-scale layering. Plagioclase dominates throughout this group of rocks, along with olivine. Zinovieff (1958) identified two features used to distinguish the five units, the general absence of layering and the presence of olivine only in small amounts at the base of each unit. Additionally, within the lowest part of the sequence, olivine constitutes *ca*. 40% of the rock, whereas in the highest part of the sequence it is only half this amount.

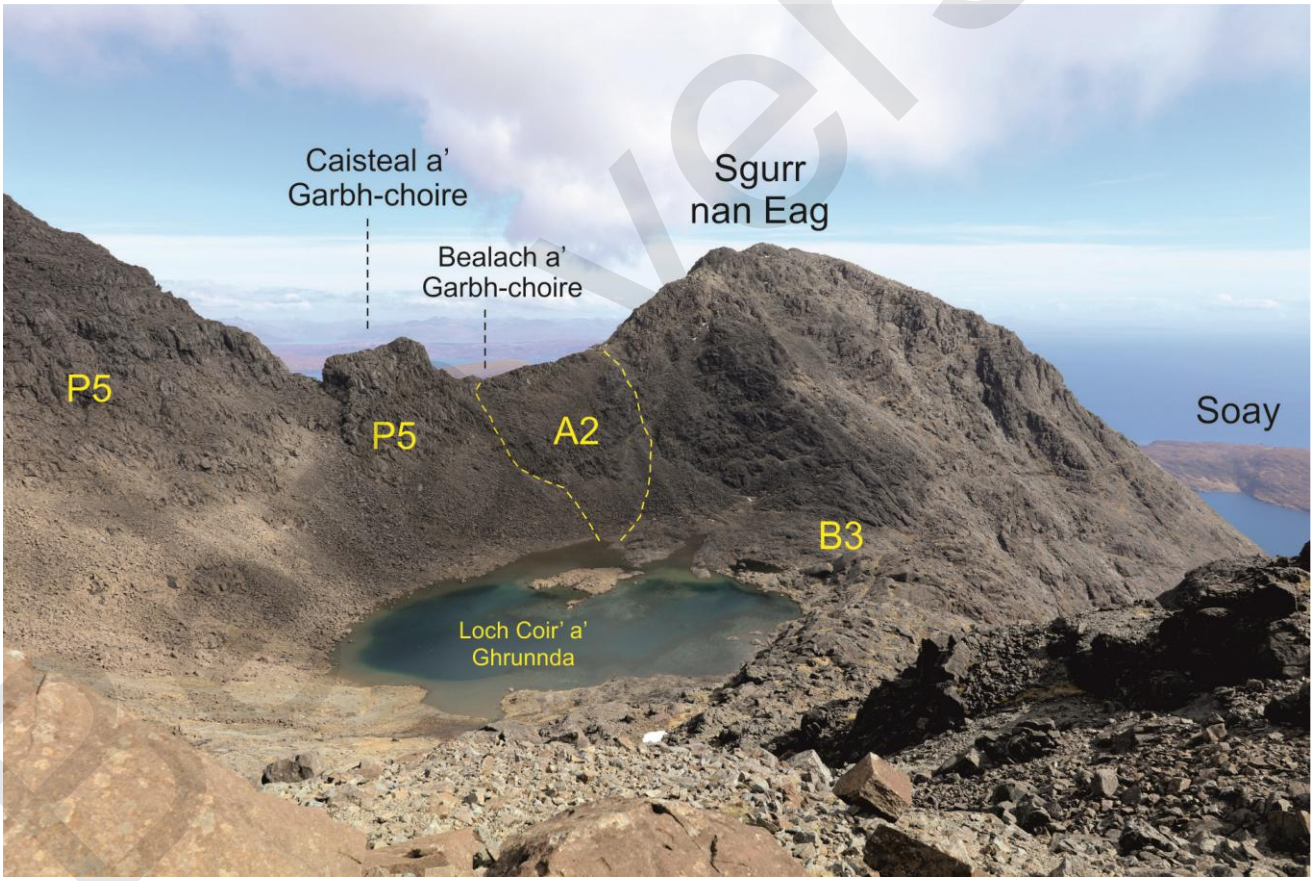


Figure 9-71: Field photograph of the area around Loch Coir' a' Ghrunnda illustrating the distribution of: B3 (the Outer Layered Bytownite Troctolites); P5 (Layered Peridotites and Bytownite Troctolites); and, A2: Unlayered micro-gabbro. View towards the south across Loch Coir' a' Ghrunnda.

Hutchison (1968) and Hutchison & Bevan (1984) concluded that the Outer Layered Bytownite Troctolites (B3) are banked up against the unlayered bytownite troctolites of the Border Group (B2, see above) and

Preview version

constitute typical cumulates deposited (or accumulated) on the margin of a funnel-shaped magma chamber. Hutchison & Bevan (1984) suggested that the Unit 1 rocks, at the lowest exposed part of the sequence, may equate with the Unit 2 bytownite troctolites of the Layered Peridotites (see below), with extensive ring-faulting bringing about the present-day field relationships. They envisage a series of events in which, after the formation of the Border Group rocks, there was a period during which olivine-rich cumulates (dunites) developed, and these were subsequently onlapped by peridotite cumulates (the Unit 1 rocks of the Layered Peridotites, see below). This was followed by the development of bytownite troctolites when plagioclase started to crystallise and fractionate. The absence of pyroxene in the Unit 1 bytownite troctolites of the Outer Bytownite Troctolites suggests that these rocks are more likely related to the Layered Peridotites (Wager & Brown 1968; Hutchison & Bevan 1977). The boundary between units 1 and 2 of the Outer Bytownite Troctolites, the latter rich in cumulus pyroxene, may represent the incoming of a new batch of magma.

With the downward faulting of the Layered Peridotites (see below), relative to the Unit 1 rocks of the Outer Bytownite Troctolites and the Border Group rocks, the present distribution of rock-types may be explained.

9.7.3.4 The Layered Peridotites

The Layered Peridotites are the oldest truly ultrabasic cumulates (rocks formed by some mechanism of crystal accumulation) associated with the CIC (Figure 9-53; Figure 9-54; Figure 9-72). They are at least 500 m thick, although the base of the sequence is not exposed, and crop out in an arcuate band running from the Allt Beag, which flows into Loch na Cuilce in the south, to Coireachan Ruadha in the north. In the lower part of An Garbh-choire, the peridotites are in direct, almost vertical, contact with Outer Gabbros (A1, see above), with the Border Group and associated bytownite troctolites (B, see above) absent. These relationships may be explained by a downward movement of a central portion of layered rocks (including the peridotites), bringing them into contact with the Outer Gabbros (A). The thermal role of the peridotites is discussed by Wager & Brown (1968), who suggest that the altered plagioclases present in the A2 micro-gabbro developed in response to the emplacement of this hot peridotite mass, although Hutchison (1966b) concluded that the clouding is a much later event.

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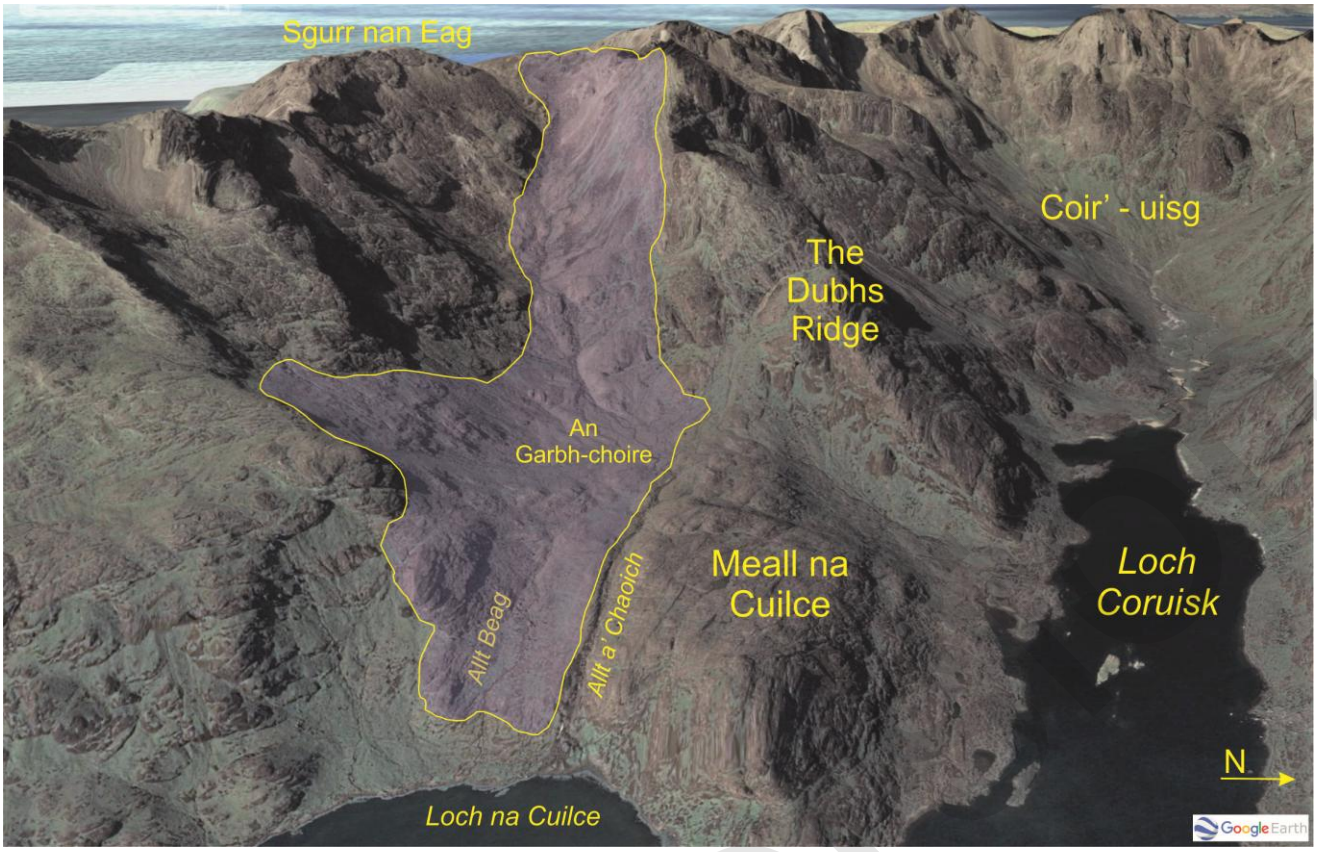


Figure 9-72: Oblique Google Earth© image of the southern part of the Cuillin, south of Loch Coruisk, indicating the approximate outcrop of the Layered Peridotites in An Garbh-choire (purple tint). View towards the west.

Details of the field relationships and petrology of the Layered Peridotites are given by Weedon (1956, 1965) and Claydon & Bell (1992). These olivine-rich rocks are relatively easily distinguished from gabbros and (plagioclase-rich) troctolites by their reddish-orange oxidation surfaces. Furthermore, the peridotites are relatively soft and easily eroded. They are readily accessed in An Garbh-choire, and in the area extending to the SE, south of the Allt a' Chaoich, but do not reach Loch na Cuilce (Figure 9-73). The outcrop continues to the west, across Caisteal a' Garbh-choire and Sgùrr Dubh an Da Bheinn into the uppermost part of Coir' a' Ghrunnda and north (east of the main Cuillin ridge) to Coireachan Ruadha. To the north of the outcrop, in the lower part of An Garbh-choire, the ground rises towards Meall na Cuilce, where rocks of the Outer Layered Bytownite Gabbros (C in Figure 9-54) crop out. The nature of the contact between the peridotites and these bytownite gabbros is outlined, below.

Weedon (1965) identified three 'zones', each named after the dominant rock-types within it: Zone I, dunites and peridotites; Zone II, 'allivalites' – now named bytownite troctolites and feldspathic peridotites (depending upon the amount of plagioclase present); and, Zone III, brecciation and segregation veins within Zone I and Zone II rocks.

Rocks of Zone I form the lowest part of the sequence, are at least 200 m thick and are exposed in the vicinity of the Allt Beag, near Loch na Cuilce (Figure 9-73). Layering is not particularly well-developed due to the dominance of equigranular olivine throughout. In the area nearest to Loch na Cuilce, the dominant rock-type is dunite (Figure 9-74), whereas to the west, further up-sequence, with the incoming of intercumulus plagioclase, are peridotites. The olivines have Mg-rich compositions, typically around Fo_{83}, and the interstitial plagioclase is An_{91} (Hutchison & Bevan 1977; Bevan 1982). Apart from olivine and plagioclase, small quantities of chrome spinel, orthopyroxene and clinopyroxene are also present, uncommonly forming distinct (1–2 cm thick) bands.

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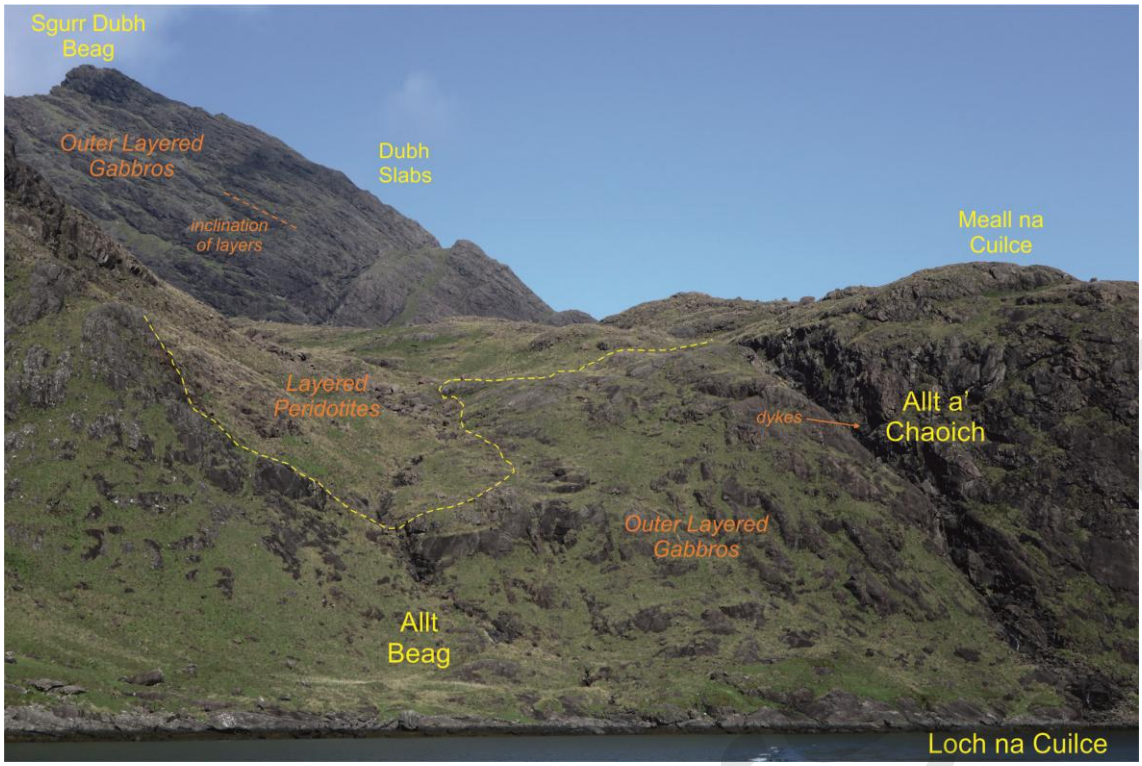


Figure 9-73: Orange-red -weathering dunites of the Zone I Layered Peridotites south (left) of the Allt a' Chaoich, which flows into Loch na Cuilce. View towards the west.



Figure 9-74: Dunites of the Zone I Layered Peridotites south of the Allt a' Choich. Compass *ca.* 10 cm long.

Zone II rocks are dominated by feldspathic peridotites and bytownite troctolites (allivalites of older literature). The presence of significant amounts of plagioclase produces excellent layering (Figure 9-75). These features are best observed between An Garbh-choire and Caisteal a' Garbh-choire. Characteristics

typically associated with cumulates are readily identified: mineralogically distinct layers, crystal size grading within layers, truncation of layers, slump structures, and 'cross-stratification'. Elongate, dendritic olivines are also present, forming a delicate interlocking structure most clearly seen on weathered surfaces. Stratification becomes less obvious further up in the Zone II sequence, whereas small, rounded autoliths (fragments of genetically related material; 'cognate xenoliths') are a common feature.



Figure 9-75: Layered feldspathic peridotites of the Zone II Layered Peridotites in the lower part of An Garbh-choire. Pole *ca*. 1 m long.

The brecciation and segregation veins of feldspathic peridotite that constitute Zone III form an important component of the Zone I rocks around the headwaters of the Allt a' Chaoich (Figure 9-76; Figure 9-77). These veins are typically 2–5 cm wide and form an anastomosing series of stringers throughout the host rocks. Their presence suggests that a significant amount of post-depositional movement of inter-cumulus magma took place through the already-formed crystal (cumulate) pile. Further evidence of disturbance of the peridotites is seen in the form of slumps and folds within the succession, and in places layers dip atypically at angles in excess of 70° towards the middle of the intrusive centre, in the vicinity of Druim Hain.

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Figure 9-76: Zone III Layered Peridotites, comprising Zone I dunite and peridotite disrupted and invaded by veins of feldspathic peridotite, below the rock barrier in An Garbh-choire. View towards the NW.



Figure 9-77: Typical Zone III veins of feldspathic peridotite in Zone I dunite, below the rock barrier in An Garbh-choire. Pole *ca*. 1 m long.

Subsequent ring-faulting along the inner margin of the Layered Peridotites most likely formed the magmatic disconformity between the Layered Peridotites and the overlying (younger) Outer Bytownite Gabbros (see above).

In a re-investigation of the Layered Peridotites, Claydon & Bell (1992) added some new observations and interpretations to the excellent, robust observations of Weedon (1965). They identified six 'chronostratigraphic' units that comprise various layered olivine-rich cumulates, ranging from dunite through to feldspathic peridotite (Figure 9-53). The structurally lowest unit (P1) is dominated by dunite and contains abundant layers rich in chrome spinel. Other units contain plagioclase, both cumulus and intercumulus, and have excellent modal layering. Autoliths (cognate xenoliths) of various ultrabasic rock-types are common and typically accentuate the layering. Unit 4 (P4) is a heterogeneous breccia comprising plagioclase-dominated blocks in a matrix dominated by olivine, and olivine-dominated blocks in a matrix dominated by plagioclase. Block types vary from anorthosite through to dunite. Such breccias are most likely to be of intrusive origin and formed by the forceful injection of ultrabasic magma into ultrabasic rocks, the latter consequently disrupted and fragmented.

A number of unusual textural varieties of peridotite, as well as structures involving various ultrabasic rocks, are preserved within the Layered Peridotites (Claydon & Bell 1992). For example, within Unit P5 on the south side of An Garbh-choire, structures that are approximately hemispherical and range in size from 15 to 200 cm across, comprise dendritic intergrowths of poikilitic intercumulus plagioclase enclosing orientated cumulus olivine (Figure 9-78). Such structures most likely formed by nucleation and growth within a crystal mush from a hydrous, aluminous, ultrabasic magma. In addition, within Unit P5, along the interface of peridotite and troctolite layers, 'fingers' of peridotite penetrate into troctolite (Figure 9-79; Figure 9-80). These structures are interpreted as evidence that hot ultrabasic magma invaded pre-existing solid troctolite and eroded it by melting. From these and other observations it is now generally accepted that thick sequences of layered ultrabasic rocks, such as the Layered Peridotites of the Cuillin Intrusive Centre, were formed through processes including crystal settling, *in situ* crystallisation, and the intrusion of sheets of hot magnesium-rich magma into pre-existing solid material of similar type.



Figure 9-78: Dendritic intergrowths of poikilitic intercumulus plagioclase enclosing orientated cumulus olivine, Layered Peridotites, south side of An Garbh-choire. Coin *ca*. 24 mm across.

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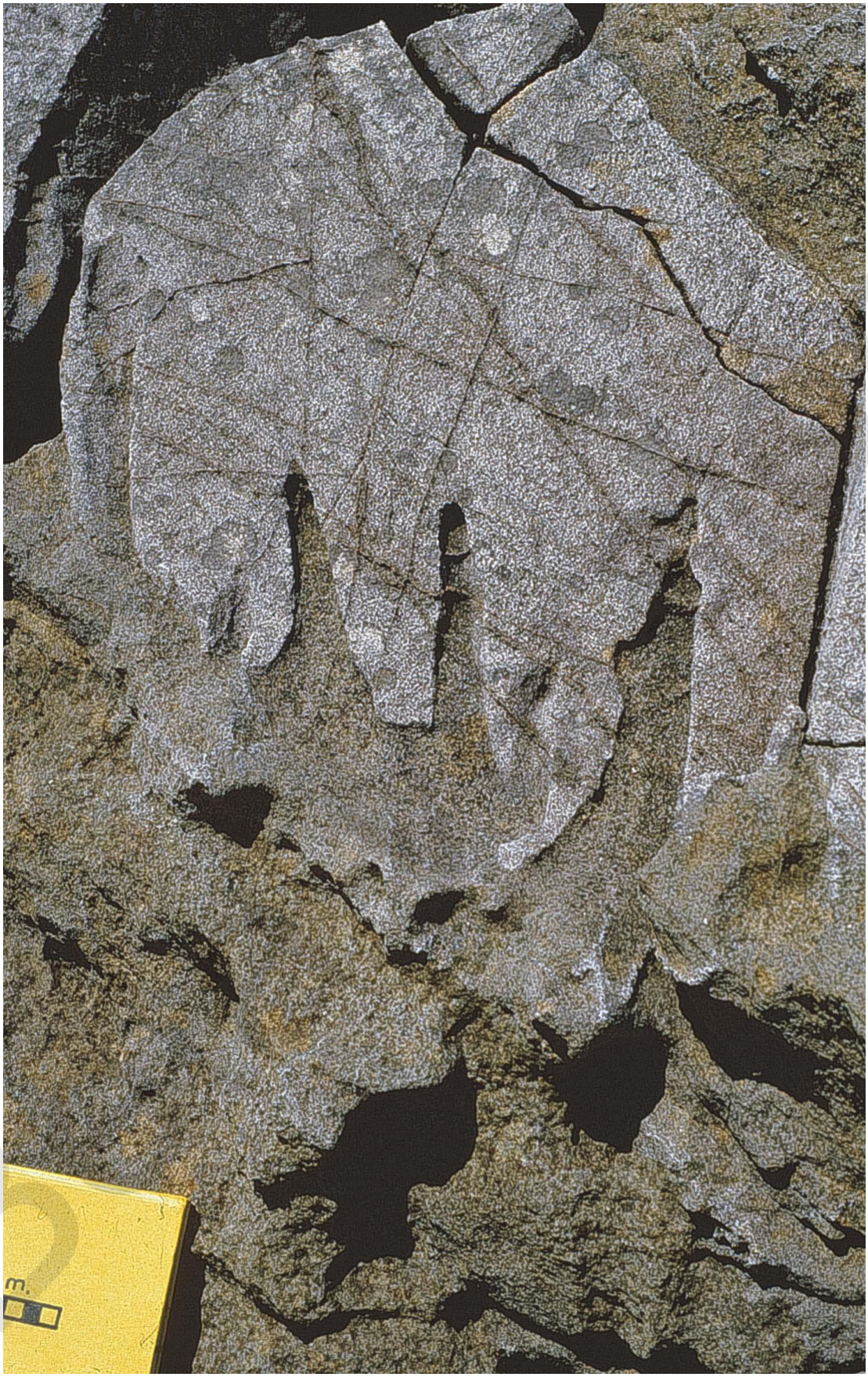


Figure 9-79: Peridotite 'fingers' penetrating troctolite within the Layered Peridotites of the Cuillin Intrusive Centre. Centimetre scale on notebook.



Figure 9-80: Irregular boundary between dark orange peridotite and pale layered troctolite in An Garbh-choire, where high-temperature peridotite magma has thermally eroded solid (crystallised) troctolite. Pole *ca.* 1 m long.

9.7.3.5 The Outer Bytownite Gabbros (C)

Detailed studies of this *ca.* 1600 m thick sequence of bytownite gabbros was undertaken by Carr (1952; 1954), Weedon (1956, 1961), Zinovieff (1958) and Jassim (1970). On the basis of Carr's pioneering excellent work, three intervals or zones are recognised, each with distinct cumulus minerals: Unit 1, plagioclase-olivine-clinopyroxene orthocumulates; Unit 2, olivine-rich adcumulates; and, Unit 3, olivine-magnetite adcumulates.

The Outer Bytownite Gabbros are exposed over a large sector of the complex, from SW of Sgùrr nan Gillean forming a crescent-shaped outcrop through Loch Coruisk, Sgùrr na Stri, Blà-bheinn and Garbh-bheinn (Figure 9-53; Figure 9-54). In the western part of the CIC, these bytownite gabbros are in contact with the Outer Bytownite Troctolites (B) and the Layered Peridotites (P) (Figure 9-81), where a narrow, unlayered, marginal facies has been identified; in the vicinity of Sgùrr na Stri and in the Blà-bheinn - Garbh-bheinn sector, this unlayered facies is in contact with hornfelsed country-rock basaltic lavas (see above). This boundary dips inwards at *ca.* 70°. Layering within the sequence dips towards the centre of the CIC, and generally increases from values of *ca.* 20° in the lowest (outer) parts of the sequence, to dips as high as 40° towards the top of the sequence, at the inner contact with the unlayered olivine-bytownite gabbros that form the ridge of Druim nan Ramh, north of Loch Coruisk (D2 in Figure 9-53 & Figure 9-54), see also below). Generally, layering is more prominent towards the top of the sequence. The most easily accessed outcrops are those investigated by Carr (1952), in a traverse through Sgùrr na Stri and Sgùrr Hain (Figure 9-85; Figure 9-86; Figure 9-87; Figure 9-88; Figure 9-89; Figure 9-90; Figure 9-91; Figure 9-92), and on The Slabs at the NE end of the Sgùrr Dubh Beag ridge (Figure 9-81; Figure 9-82; Figure 9-83; Figure 9-84).

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Figure 9-81: Contact at break in slope between orange-weathered Layered Peridotites (near ground) and the Outer Bytownite Gabbros (high ground, left), north side of An Garbh-choire, below Sgùrr Dubh Beag.



Figure 9-82: Layered Outer Bytownite Gabbros (C) forming the The Slabs, SW of the NW end of Loch Coruisk.

Preview



Figure 9-83: Layered Outer Bytownite Gabbros (C) forming the The Slabs, SW of the NW end of Loch Coruisk.



Figure 9-84: Detail of the Layered Outer Bytownite Gabbros (C) forming the The Slabs, SW of the NW end of Loch

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Figure 9-85: Layered Outer Bytownite Gabbros (C) north of Loch nan Leachd (northern end of Loch Scavaig), between the Scavaig River and the Bad Step. View towards the north.



Figure 9-86: Layered Outer Bytownite Gabbros (C) at the SE end of Loch Coruisk. View towards the east.

Preview version



Figure 9-87: Detail of the Layered Outer Bytownite Gabbros (C) at the SE end of Loch Coruisk. View towards the east.

Beta version



Figure 9-88: Detail of the layered Outer Bytownite Gabbros (C) north of Loch nan Leachd, between the Scavaig River and the Bad Step, with dark layers rich in olivine and pale layers rich in plagioclase. Note orange-weathered peridotite xenolith at top left. Pole *ca*. 1 m long.

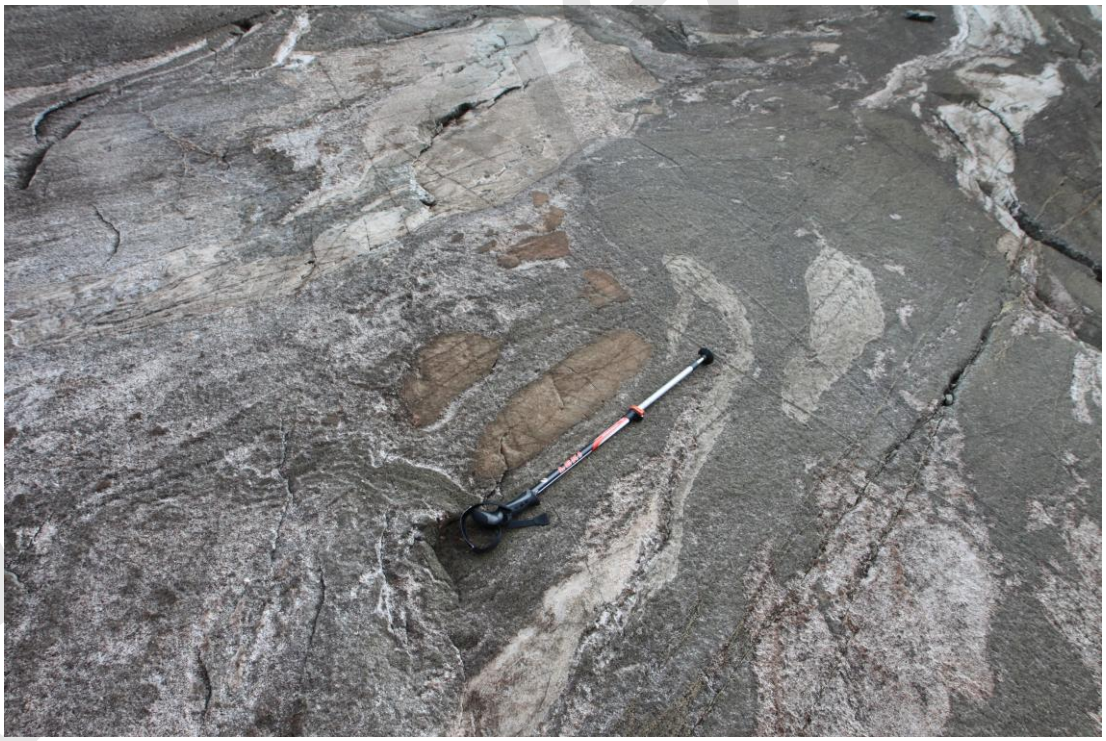


Figure 9-89: Detail of the layered Outer Bytownite Gabbros (C) north of Loch nan Leachd, between the Scavaig River and the Bad Step, with elongate blocks/xenoliths of orange-weathered peridotite and pale troctolite. The host bytownite gabbro is relatively heterogeneous, with disrupted layering/banding and feldspathic veins. Pole *ca*. 1 m long.



Figure 9-90: Well-developed mineral layering in the Outer Bytownite Gabbros (C) on Meall na Cuilce (between Loch Coruisk and Loch na Cuilce). Note xenoliths of orange-weathered peridotite at top left and the general northerly (top-right to bottom-left) dip of layering in the Outer Bytownite Gabbros *and* dolerite/basalt cone-sheets on Sgùrr na Stri in the distance. Shaft of hammer *ca*. 30 cm long.



Figure 9-91: Layered Outer Bytownite Gabbros at the summit of Sgùrr na Stri. View is towards the NE, with Blà-bheinn in the distance. Layering inclined towards the NW.

Proof version



Figure 9-92: Exposure of layered Outer Bytownite Gabbros at the summit of Sgùrr na Stri. View towards the north. Pole *ca.* 1m long.

Cryptic variation is present, to a minor extent, within these rocks, with plagioclase ranging from An_{75} in the lowest exposed part of Unit 1, to An_{67} at the top of Unit 3. Likewise, olivine varies from Fo_{74} to Fo_{67}. A significant and distinctive feature of these cumulates, especially in units 2 and 3, is the presence of 'calcic-phase phenocrysts' of plagioclase, with a relatively constant composition of An_{85} (Carr 1952). It is likely that their presence indicates the incoming of a new batch of crystal-laden magma at that stage in the development of the intrusive centre.

Carr (1952) also discusses the presence of various types of 'blockstuff' (i.e. xenoliths) within the Outer Bytownite Gabbros. These are principally blocks of dunite and peridotite, but also includes bytownite troctolite, bytownite gabbro, gabbro, dolerite and basalt, and are found particularly in the Meall na Cuilce area (Weedon 1956, 1961). Their incorporation into the Outer Bytownite Gabbros suggests that disturbance of already-consolidated material within the intrusive centre took place during magma emplacement/intrusion. This may have involved faulting, with (central) subsidence or marginal uplift taking place.

The inner margin of the Outer Bytownite Gabbros is marked by the strongly discordant D2 unlayered olivine-bytownite gabbro forming the ridge of Druim nan Ramh, which cuts across rocks of all three units.

Brandriss *et al.* (2014) concluded on the basis of a detailed investigation of the exposures illustrated in Figure 9-85 & Figure 9-88, that the layered character of the Outer Bytownite Gabbros is the result of repeated influxes of plagioclase porphyritic basaltic magma into the magma chamber, depositing their crystals on the contemporaneous floor of the chamber and producing what they refer to as ‘coarse-grained massive gabbro.’ During periods between these influx events, ‘normal’ crystal settling processes

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or *in situ* crystallisation produced the intervening layers of 'fine-grained laminated gabbro.' Interstitial melts trapped between the main cumulus minerals in both types of gabbro were partially expelled during compaction, typically more efficiently from the laminated gabbro. Brandriss *et al*. (2014) infer from geochemical data that the magma chamber was sheet-like and of relatively small volume. This model is essentially the same suggested by Carr (1952), some sixty years previously.

9.7.3.6 The Unlayered Olivine-bytownite Gabbro (of Druim nan Ramh) (D)

The unlayered olivine-bytownite gabbro that crops out on the ridge of Druim nan Ramh is a coarse-grained rock devoid of layering and has a semi-circular outcrop that separates the Outer and Inner groups of the CIC (Figure 9-53; Figure 9-54; Figure 9-93; Figure 9-94; Figure 9-95; Figure 9-96; Figure 9-97; Figure 9-98; Figure 9-99). It was first described by Carr (1952), who referred to it as an 'invading eucrite'. Subsequent work by Zinovieff (1958) inferred that this unit is a ring-shaped intrusion and suggests that the rocks interior and exterior to the intrusion can be correlated. On this basis, Wager & Brown (1968) suggested that large displacements of a central block took place prior to, and during, the injection of the unlayered olivine-bytownite gabbro. Such displacements, however, would have to be of the order of 1,000 m in an upward direction - contrary to the perceived general trend of central subsidence throughout the evolution of the intrusive centre.

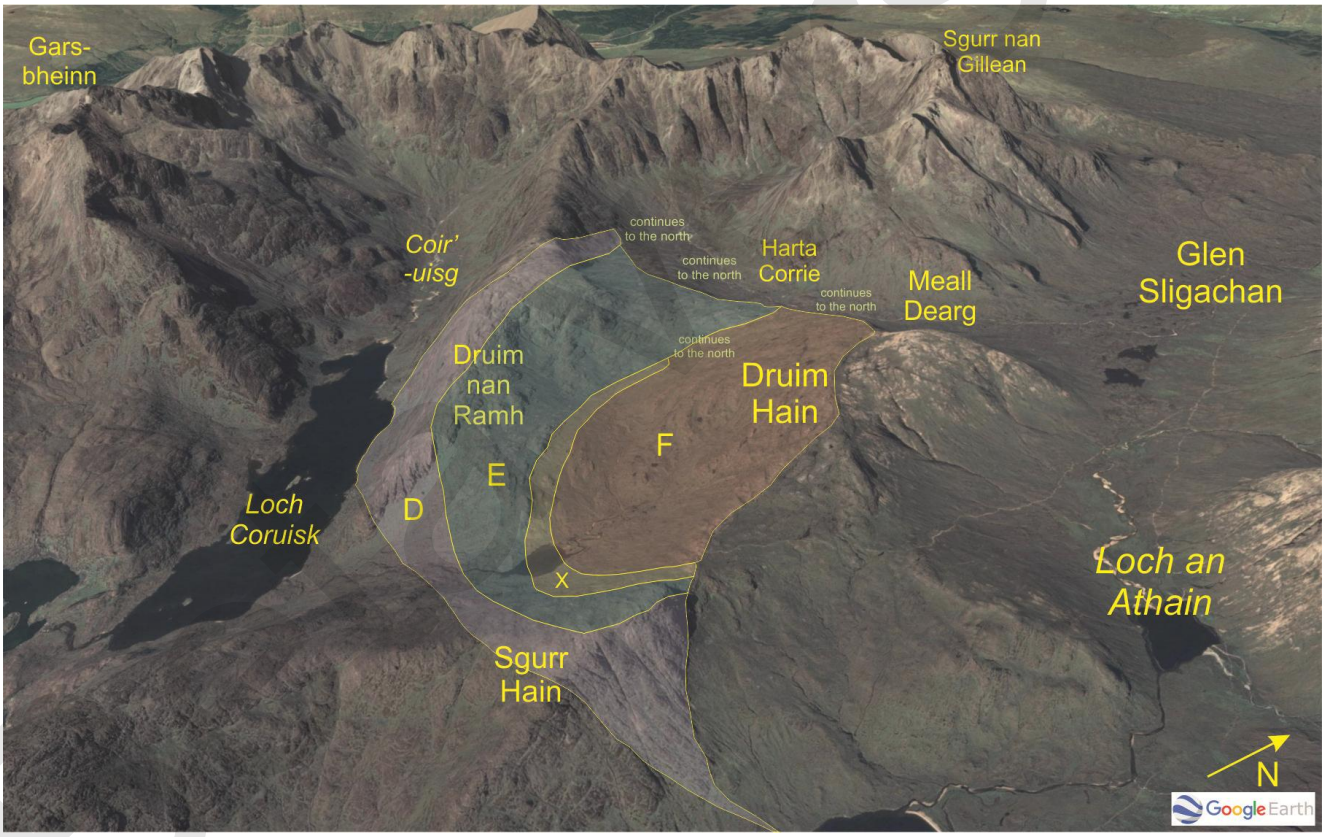


Figure 9-93: Oblique Google Earth© image illustrating the outcrop of the unlayered olivine-bytownite gabbro of Druim nan Ramh (D), the Inner Bytownite Troctolites (E), the Inner Gabbros (F) and a zone of intrusion breccia (X). View towards the west. Oblique projection causes some distortion of outcrop geometry.

Pre-submission



Figure 9-94: The Druim nan Ramh ridge from the SE end of Loch Coruisk.



Figure 9-95: The Druim nan Ramh ridge from the Allt a' Choire Riabhaich at the SE end of Loch Coruisk.

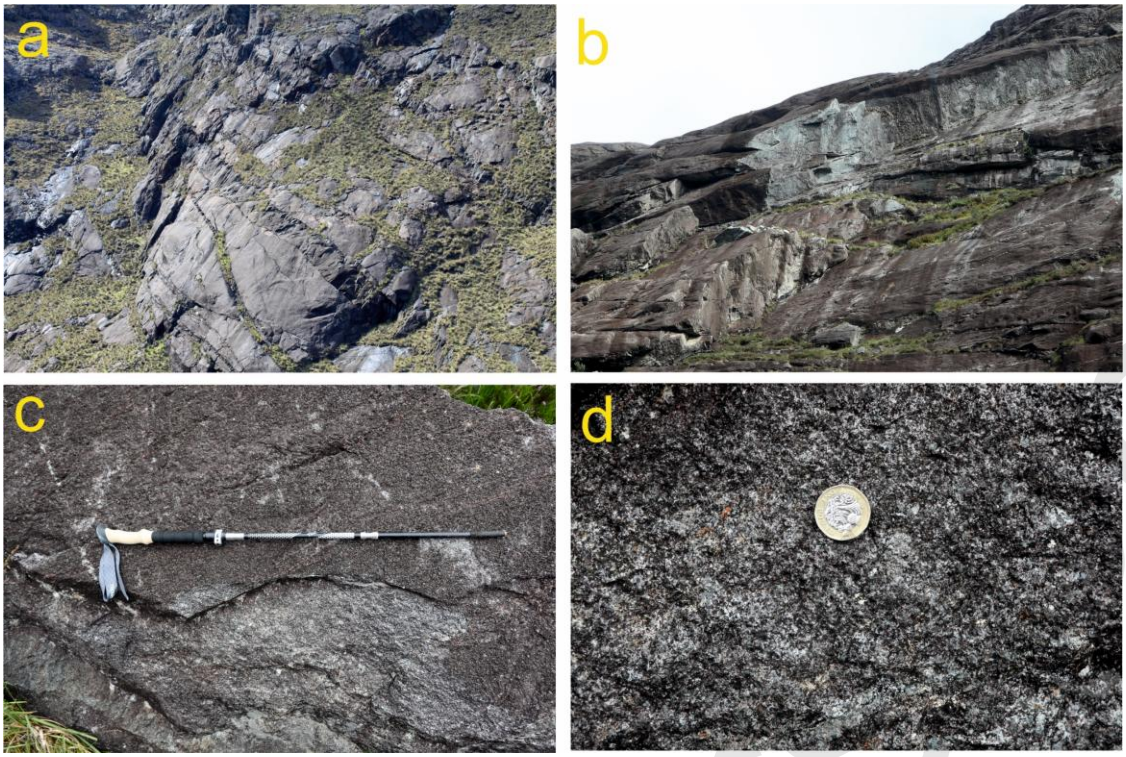


Figure 9-96: Field images of the Unlayered Olivine-bytownite Gabbro (D): (a) intruded by dolerite cone-sheets, west of the Allt a' Choire Riabhaich (NE of Loch Coruisk); (b) collapsed surface, NE of Loch Coruisk; (c) typical weathered and fresh surfaces, pole *ca*. 1 m long; and, (d) typical fresh surface, coin *ca*. 24 mm across.



Figure 9-97: Cross-cutting Unlayered Olivine-bytownite Gabbro (D), south of the Sgùrr Hain summit. Pole *ca*. 1 m long.

Preview



Figure 9-98: Detail of cross-cutting Unlayered Olivine-bytownite Gabbro (D) in the Sgùrr Hain summit area, with conspicuous plates of dark green clinopyroxene in an ophitic texture with smaller pale crystals of plagioclase. Coin *ca*. 24 mm across.



Figure 9-99: Fragments of (oxidised orange-weathered) magnetite-bearing gabbro within the Inner Cross-cutting Bytownite Gabbro in the Sgùrr Hain summit area. Pole *ca*. 1 m long.

An alternative hypothesis is that this unlayered olivine-bytownite gabbro represents a marginal group of rocks and marks the onset of a second major phase of intrusive activity within the CIC, related to the development of the Inner Bytownite Troctolites (E, see below) and the Inner Gabbros (F, see below).

Irrespective of its status, the unlayered olivine-bytownite gabbro of Druim nan Ramh has almost vertical contacts and an average width, at the present level of erosion, of *ca*. 200 m. It is truncated to the SE, on the west side of Srath na Crèitheach, by volcaniclastic rocks, and to the north by the Marsco Granite of the Western Red Hills Intrusive Centre. It is best observed on Druim nan Ramh. The outer contact is extremely irregular, consisting of veins injected into the Outer Bytownite Gabbros. Zinovieff (1958) noted that individual veins are commonly enriched in one mineral, for example, olivine or pyroxene, suggesting that the magma was introduced as pulses of crystal-laden mush. Progressing inwards, a xenolithic facies is encountered, containing blocks/xenoliths of material from outer units, particularly bytownite troctolite and bytownite gabbro. The inner contact is much sharper and it is possible to distinguish the unlayered olivine-bytownite gabbro from the Inner Bytownite Troctolites (Zinovieff (1958).

9.7.3.7 The Inner Bytownite Troctolites and Inner Bytownite Gabbros (E)

Very little published information is available on the Inner Bytownite Troctolites (Figure 9-53; Figure 9-54; Figure 9-100). According to Zinovieff (1958), three units can be identified, which it is suggested are simply a repetition of part of the Outer Bytownite Troctolites (B, see above). The estimated thickness of the sequence is of the order of 500 m, and individual units consist of plagioclase-pyroxene cumulates at the base, grading upwards into finely laminated plagioclase-olivine cumulates. Where layering is present, it dips towards a focal point similar to that deduced for units of the outer sequences, i.e. below Meall Dearg, at the southern end of Glen Sligachan.

The Inner Bytownite Gabbros are of the order of 450 m thick and are exposed in Harta Corrie, where in direct contact with the Inner Bytownite Troctolites, which they overlie at a steep angle (Zinovieff 1958). Layering is poorly developed, and these rocks are truncated to the east by a large mass of breccia on Meallan Dearg and to the NE by a faulted contact with the younger Inner Gabbros (F, see below). Poor exposure, plus the effects of later intrusions, largely prevents a detailed investigation of these rocks.



Figure 9-100: Field image of the Inner Bytownite Gabbros (E) on the NE side of Druim nan Rahm. Pole *ca*. 1 m long.

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9.7.3.8 The Inner Gabbros (F)

The Inner Gabbros constitute the youngest group of cumulates preserved within the CIC. They are best exposed on the ridge of Druim Hain, west of Srath na Crèitheach, as, to the south, in Coire Riabhach, exposure is poor (Figure 9-101; Figure 9-102). Within the latter region, however, it is possible to identify a vertical shatter zone, *ca*. 50 m wide, along which (it has been suggested by Wager & Brown (1968) that) downward movement of the Inner Gabbros has brought them to their present position. Carr (1952) estimated that this displacement is of the order of 300 m. Rocks within this zone are intensely crushed, resulting in a fragmental rock, a breccia that contains obvious fragments of peridotite. These shattered rocks are also cut by numerous irregular intrusions of dolerite and basalt.

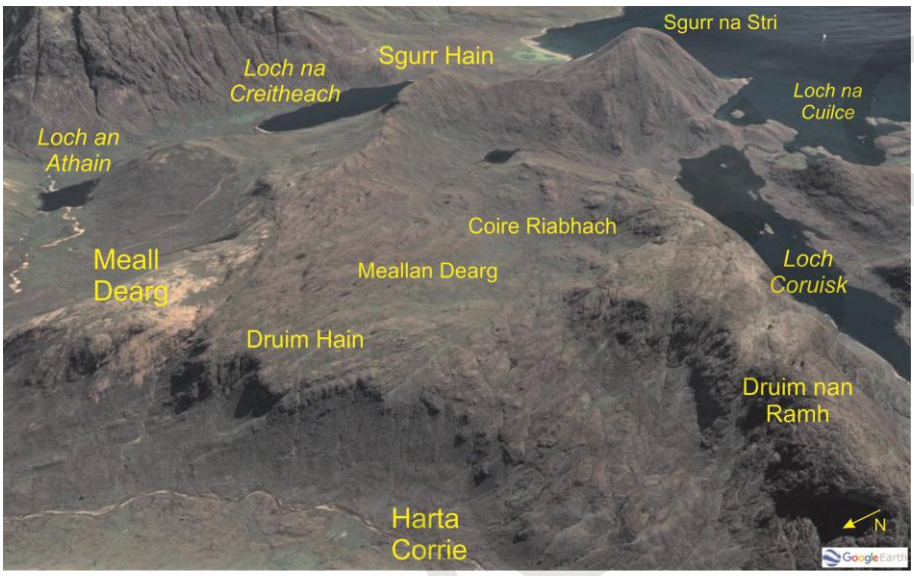


Figure 9-101: Oblique Google Earth© image of the Druim Hain area.



Figure 9-102: Inner Gabbros (F) on Druim Hain. View is towards the NW, with Sgùrr nan Gillian as the right-hand pyramidal summit in the distance.

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A recognisable sequence of gabbros, at least 750 m thick, is preserved on Druim Hain (Figure 9-103; Figure 9-104; Figure 9-105; Figure 9-106).

The arcuate distribution of the layering is easily recognised, with the focal point lying below Meall Dearg to the north (Figure 9-101). The lowest rocks of the sequence show the weakest development of layering and constitute a thickness of at least 200 m. The incoming of a distinct lamination marks the main portion of the layered sequence, at least 300 m thick. These rocks exhibit excellent rhythmic layering, uncommonly showing mineralogical grading, with magnetite enrichment at the base of individual units, passing upwards into plagioclase-rich tops. The dip of the layers ranges from *ca*. 30° in the lower parts of the sequence, up to 70° at the top of the preserved sequence. Minor normal cryptic variation is present within both the plagioclases and the olivines, with ranges of $An_{58–69}$ and $Fo_{58–66}$, respectively. Apatite also occurs as a cumulus phase, indicating that the magmas involved achieved relatively evolved compositions. The highest exposed rocks (SSE of Meall Dearg) have uncommon developments of coarse pegmatitic facies.



Figure 9-103: Steeply inclined, layered Inner Gabbros (F) on Druim Hain, beside unnamed lochan SW of Meall Dearg. Iain Allison for scale.



Figure 9-104: Steeply inclined, layered Inner Gabbros (F). View towards Blà Bheinn. Pole *ca*. 1 m long.

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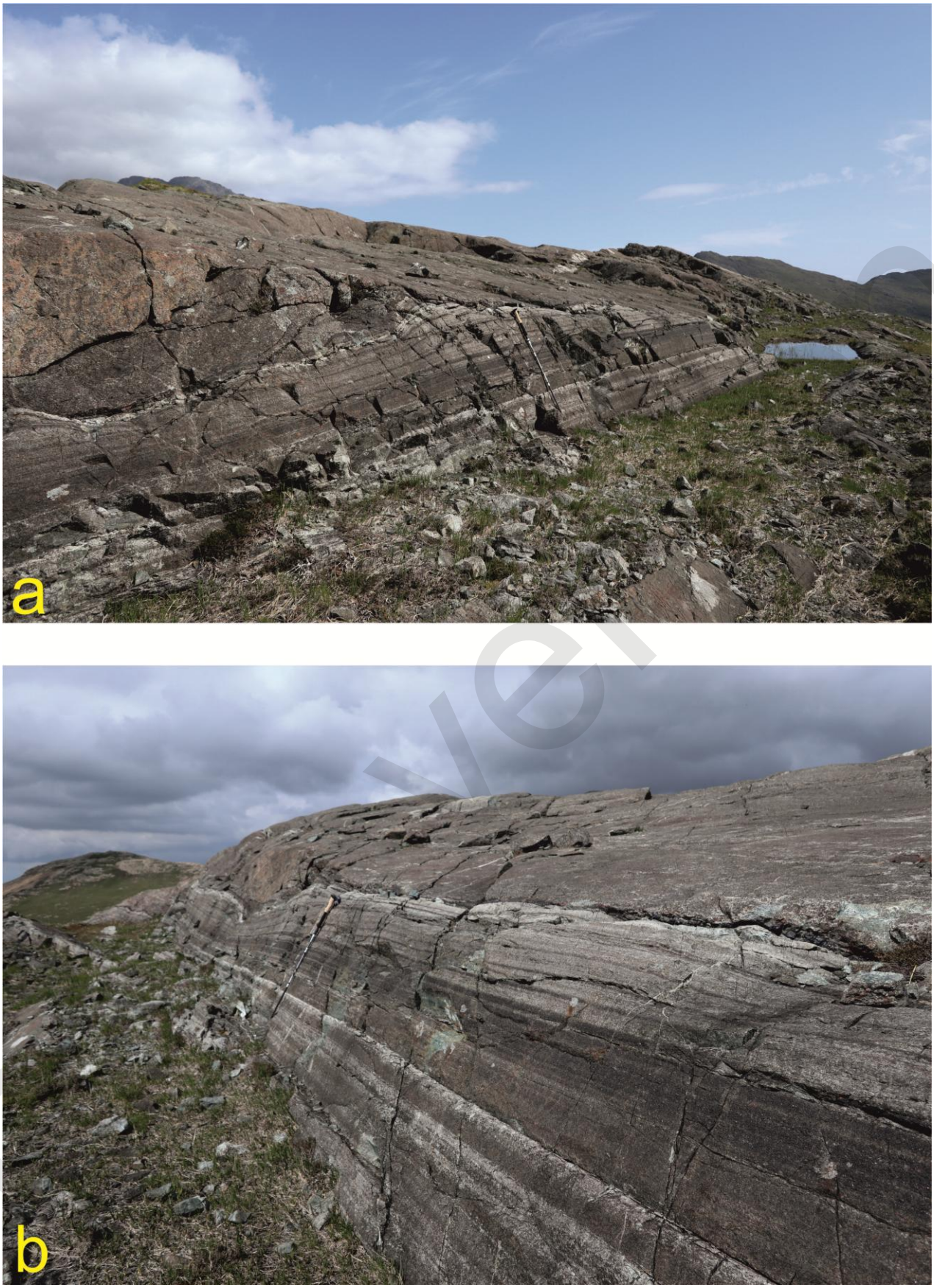


Figure 9-105: Steeply inclined, layered Inner Gabbros (F) on Druim Hain: (a) towards the NE; and, (b) towards the NW, with Meall Dearg in the distance (left). Pole *ca*. 1 m long.

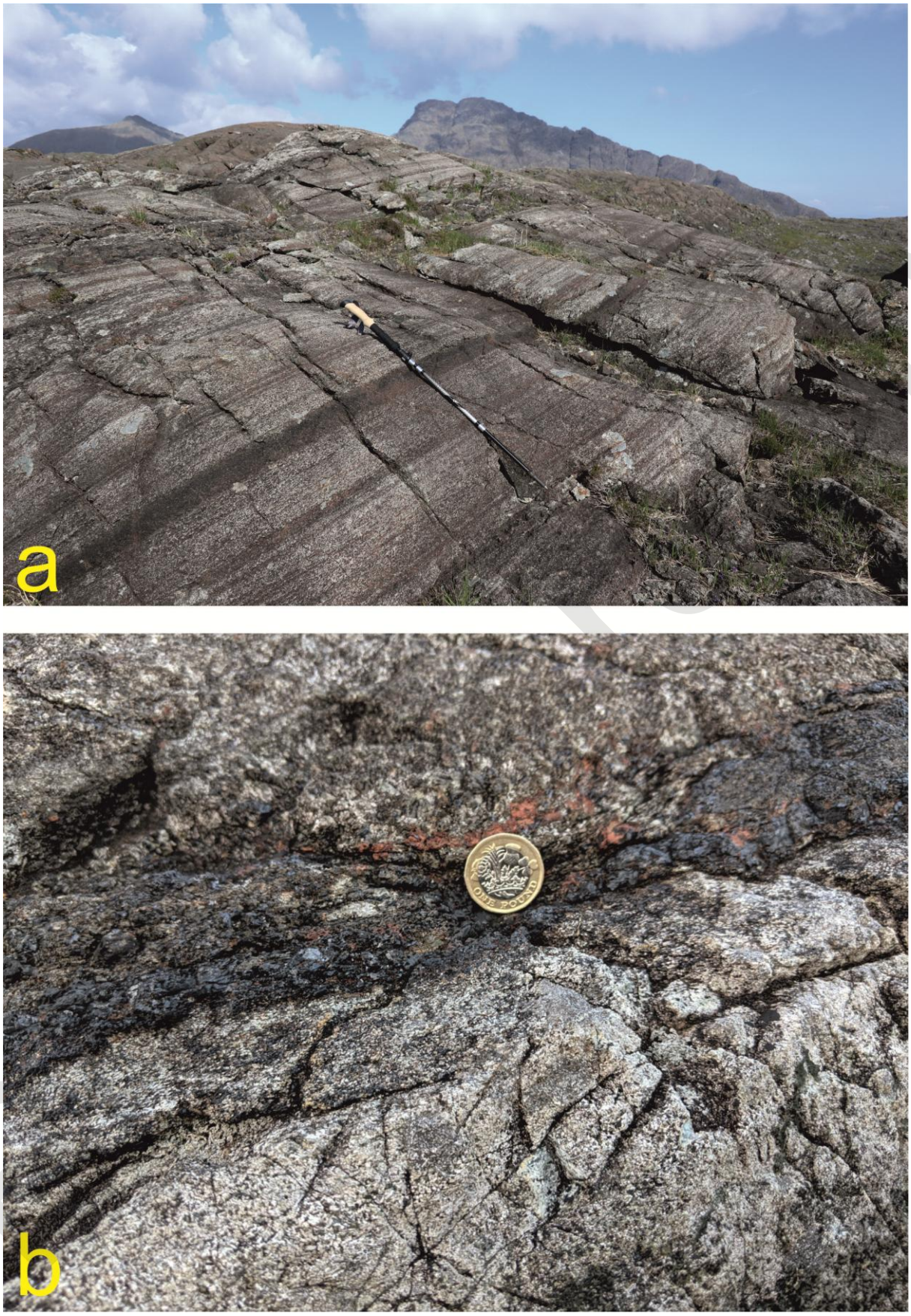


Figure 9-106: Inner Gabbros (F) on Druim Hain, with: (a) a prominent dark layer rich in magnetite, pole *ca*. 1 m long; and, (b) a thin layer dominated by magnetite, coin *ca*. 24 mm across.

The Inner Gabbros contain calcium-rich plagiocases (An_{85}), similar in character/composition to plagioclases ('calcic-phase phenocrysts') in the Outer Bytownite Gabbros (see above), especially units 2 and 3. Their presence suggests that the supply of new batches of crystal-laden (plagioclase-porphyritic) magma may have continued until at least this stage in the evolution of the intrusive centre. Xenoliths present within these gabbros include peridotite, bytownite gabbro and dolerite.

Any coarse-grained basic or ultrabasic rocks that may have formed at a later stage than the (preserved portion of the) Inner Gabbros have subsequently been removed by erosion.

9.7.4 Volcaniclastic Pipes

Zinovieff (1958) describes over forty pipe-like masses of breccia throughout the western portion of the CIC (Figure 9-107). Other similar material has been identified in the eastern sector of the complex (Dundas, in a personal communication to J.D. Bell 1976), as well as to the south of the complex, on the north side of the Soay Sound (Harker 1904).

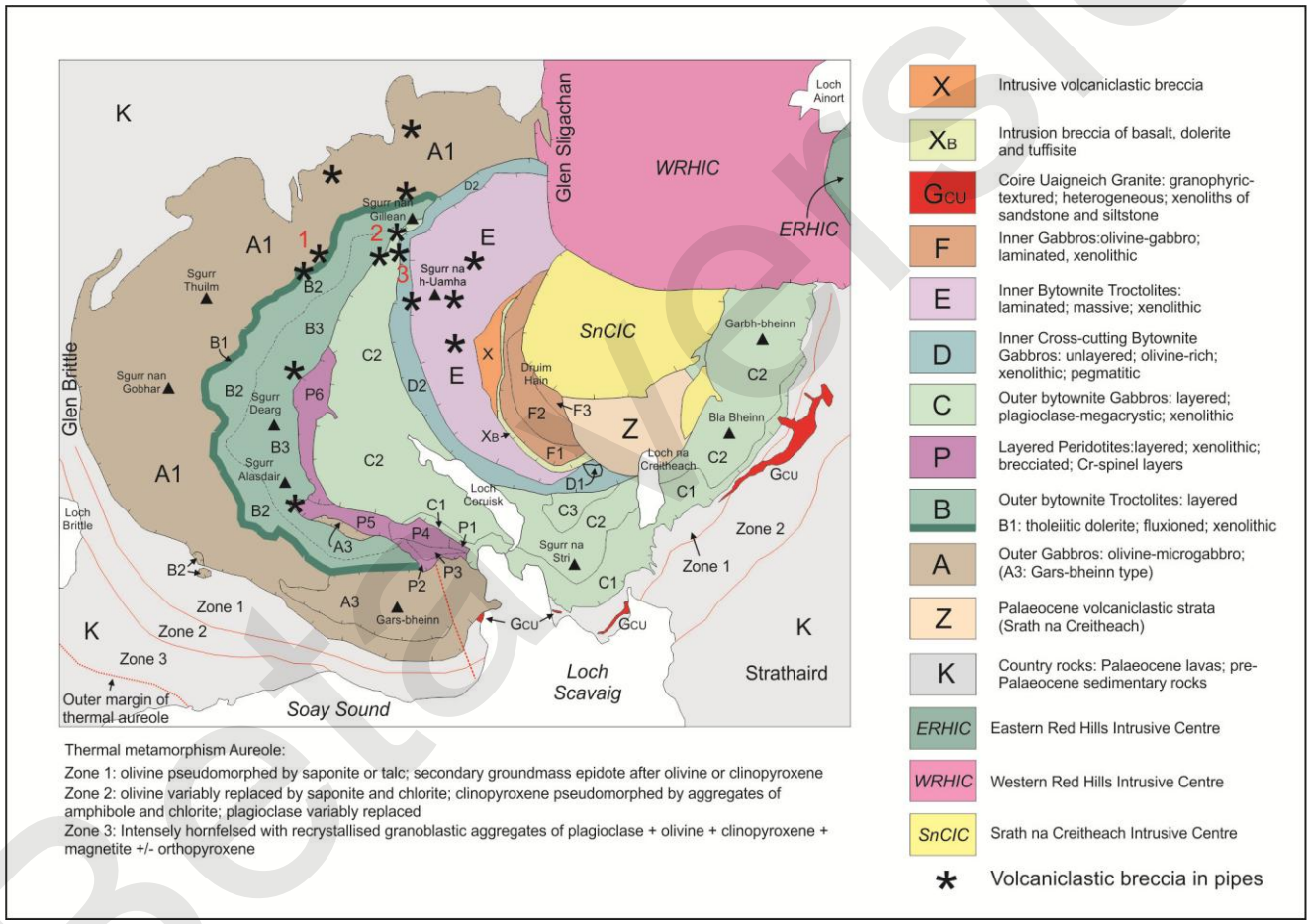


Figure 9-107: Simplified geological map showing the distribution of the (main) volcaniclastic pipes intruded into the CIC. 1, Coire na Creiche; 2, Sgùrr nan Gillean; 3, Lotta Corrie (see main text).

These masses of breccia pierce, and hence post-date, the various coarse-grained basic and ultrabasic rocks of the CIC. They are readily identified in the field by their distinctly fragmental appearance and consist of blocks of basic and ultrabasic rock-types set in a doleritic or fine-grained fragmental matrix (Figure 9-108; Figure 9-109).

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Figure 9-108: Field image of a volcaniclastic pipe in Harta Corrie, with angular blocks of basalt and dolerite in a basaltic matrix. Pole *ca.* 1 m long.



Figure 9-109: Field image of a volcaniclastic pipe in Harta Corrie, with angular blocks of basalt and dolerite in a doleritic matrix. Coin *ca.* 24 mm across.

Zinovieff (1958) identified three main groups of pipes: (1) the Coire na Creiche Group; (2) the Sgùrr nan Gillean Group; and, (3) the Lota Corrie Group (Figure 9-107). Other smaller, geographically localised groups are present throughout the Cuillin.

The largest single outcrop is on Meallan Dearg, south of the lower part of Harta Corrie. Close to the outcrop margin, the most prominent blocks are of fine-grained fragmental rock, grading over a short distance, inwards, into a coarse, block-dominated breccia. The dominant block-types are of bytownite troctolite, bytownite gabbro and gabbro, commonly angular, set in a predominantly doleritic, but in places finer-grained, fragmental, matrix. Crush zones are common.

The size, degree of rounding and sorting of the blocks within these pipe-like structures appears to depend upon the structural height at which the material occurs. Zinovieff (1958) proposed the following simplistic model, consistent with the limited observations made, to explain the various features. First, magma (dyke) injection causes brecciation of the coarse-grained (igneous) country-rocks, whilst under compression. Increased vapour pressure due to rapid cooling of this magma causes fluidisation of the blocks that have formed, transporting them upwards in a coherent fashion. During this process, abrasion of blocks, mixing, and further brecciation takes place, resulting in the development of fine-grained matrix material. Material of this type penetrates upwards to the highest structural levels (for example, on the upper parts of Sgùrr nan Gillean). Finally, the fluidised masses collapse, due to the lack of a sufficient pressure gradient to drive the system, resulting in the preserved textural characteristics.

The pipe on the southern slopes of Sgùrr na h-Uamha shows many of the features outlined above (Zinovieff 1958). At its base, the dominant material is a coarse-grained breccia, with numerous associated basaltic and doleritic dykes. The matrix constitutes *ca.* 10% of the total volume of the pipe. This passes upwards into a breccia with more rounded clasts, set in a fine-grained fragmental matrix. Material in the uppermost preserved part of the pipe is highly vesiculated, suggesting a final escape of gas from the system.

9.7.5 Cone-sheets

Cone-sheets intrude the coarse-grained basic and ultrabasic rocks of the CIC, as well as the Coire Uaigneich Granite (see below) and parts of the surrounding country-rocks (Figure 9-110; Figure 9-111; Figure 9-112; Figure 9-113; Figure 9-114; Figure 9-115; Figure 9-116). They have a focal point below Meall Dearg (at an estimated depth of 2–3 km), at the southern end of Glen Sligachan. The Skye cone-sheets were first investigated by Harker (1904), who referred to them as inclined basic sheets. Subsequent work by Bailey *et al.* (1924) on Mull led to the use of the term cone-sheet.

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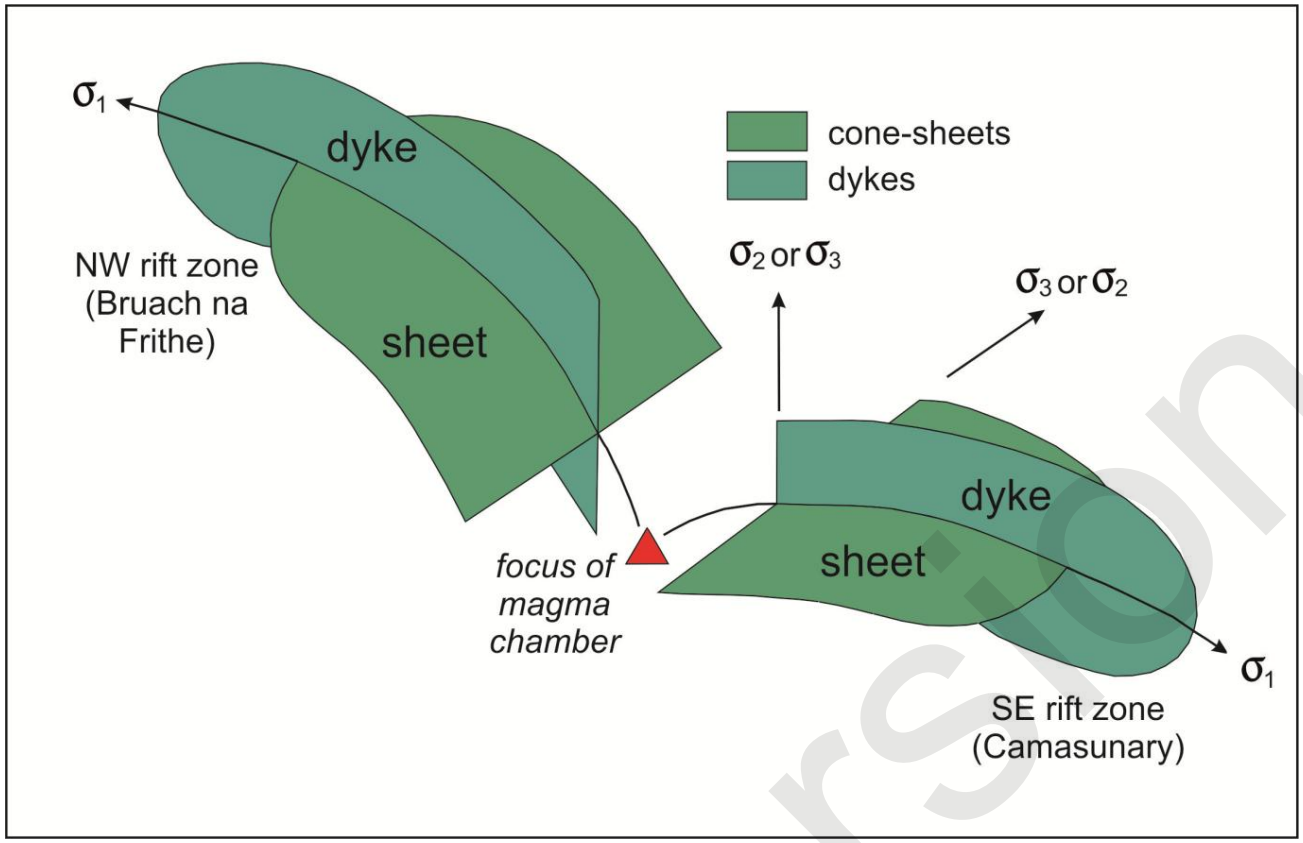


Figure 9-110: Relationship between cone-sheets and a dyke swarm. Dykes are injected when the principal deviatoric stress axis is horizontal, and cone-sheets are injected when the principal deviatoric stress axis is vertical (after Walker 1993b and Emeleus & Bell 2005).

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Figure 9-111: Cone-sheet intruded into Outer Bytownite Gabbros at the summit of Sgùrr na Stri, inclined towards the NW (top-right to bottom-left), with well-developed cooling joints. Pole *ca.* 1 m long.



Figure 9-112: Orange-weathering olivine dolerite cone-sheets intruded into Outer Bytownite Troctolites on Sgùrr an Fhionn-Choire, Am Bsasteir and Sgùrr nan Gillian, northern Cuillin, Skye.

Cone-sheets are most common in the units immediately exterior and interior to the unlayered olivine-bytownite gabbro of Druim nan Ramh (see above), where they dip inwards at an angle of 35–40°. Exterior to the olivine-bytownite gabbro, in 'lower stratigraphic/lithodemic units', they dip at shallower angles (10–20°), whereas in 'higher stratigraphic/lithodemic units' they dip at higher angles (50–65°). In general, the cone-sheets are concordant, or nearly so, with any layering present within the host basic and ultrabasic units of the CIC. They also occur within the adjacent country-rocks. (Figure 9-113).

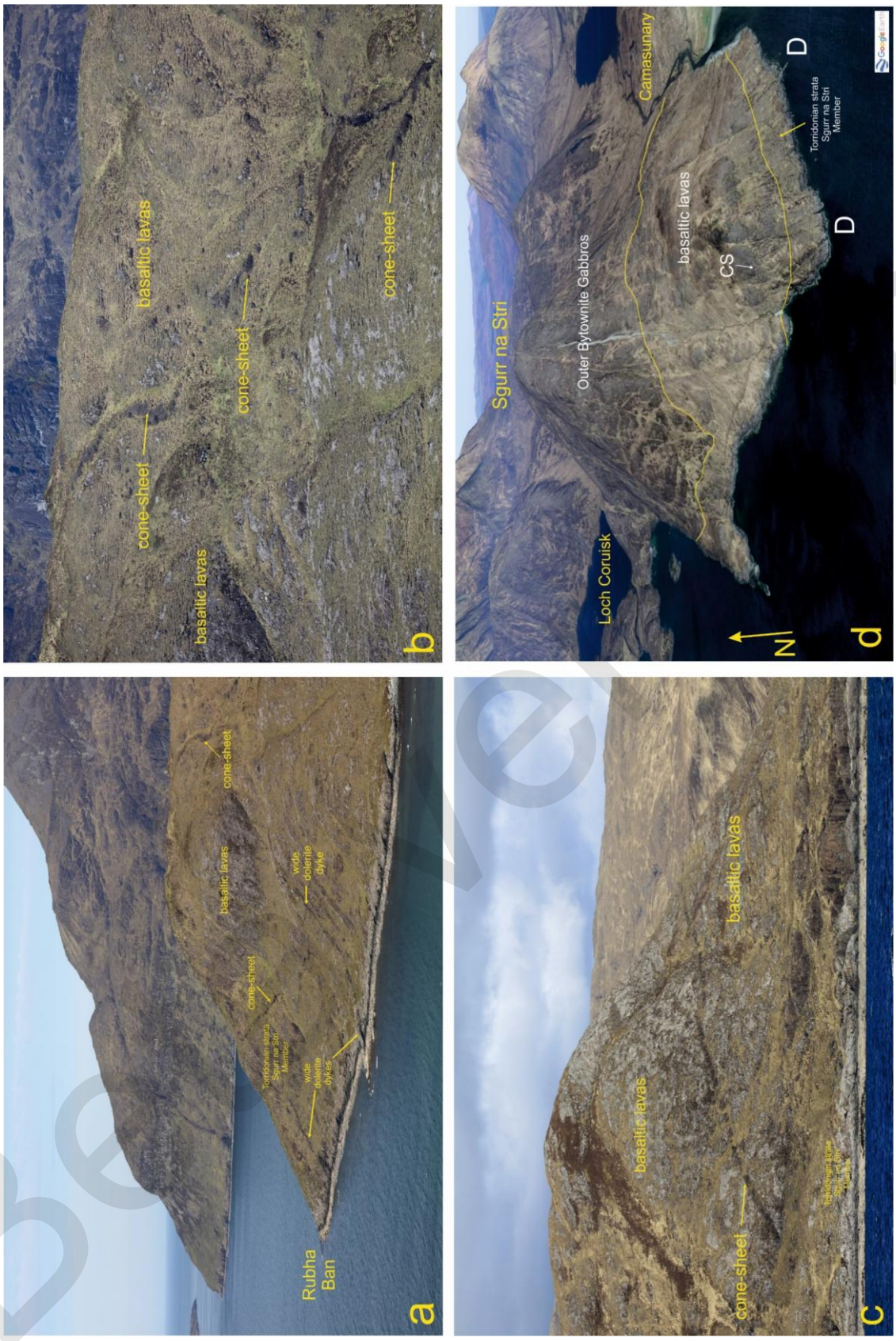


Figure 9-113: Two thick cone-sheets intruded into Torridonian strata and basaltic lavas north of Rubha Bàn on the west side of Camasunary Bay. These cone-sheets are located in the 'SE Rift Zone'. (a) & (b) view towards the west; (c) view towards the NE; (d) Oblique Google Earth© image, with main units labelled, D: dyke; CS: cone-sheet.



Figure 9-114: Cone-sheets forming distinct, inclined featuring on the south side of Sgùrr na Stri. View towards the east from Loch Scavaig. CS, cone-sheets.



Figure 9-115: Cone-sheets forming distinct, inclined featuring in the northern Cuillin, from Sgùrr an Fheadain (left) to Am Bàsteir (right), with the conspicuous, inclined Basteir Tooth. View towards the north from An Garbh-choire

Preview

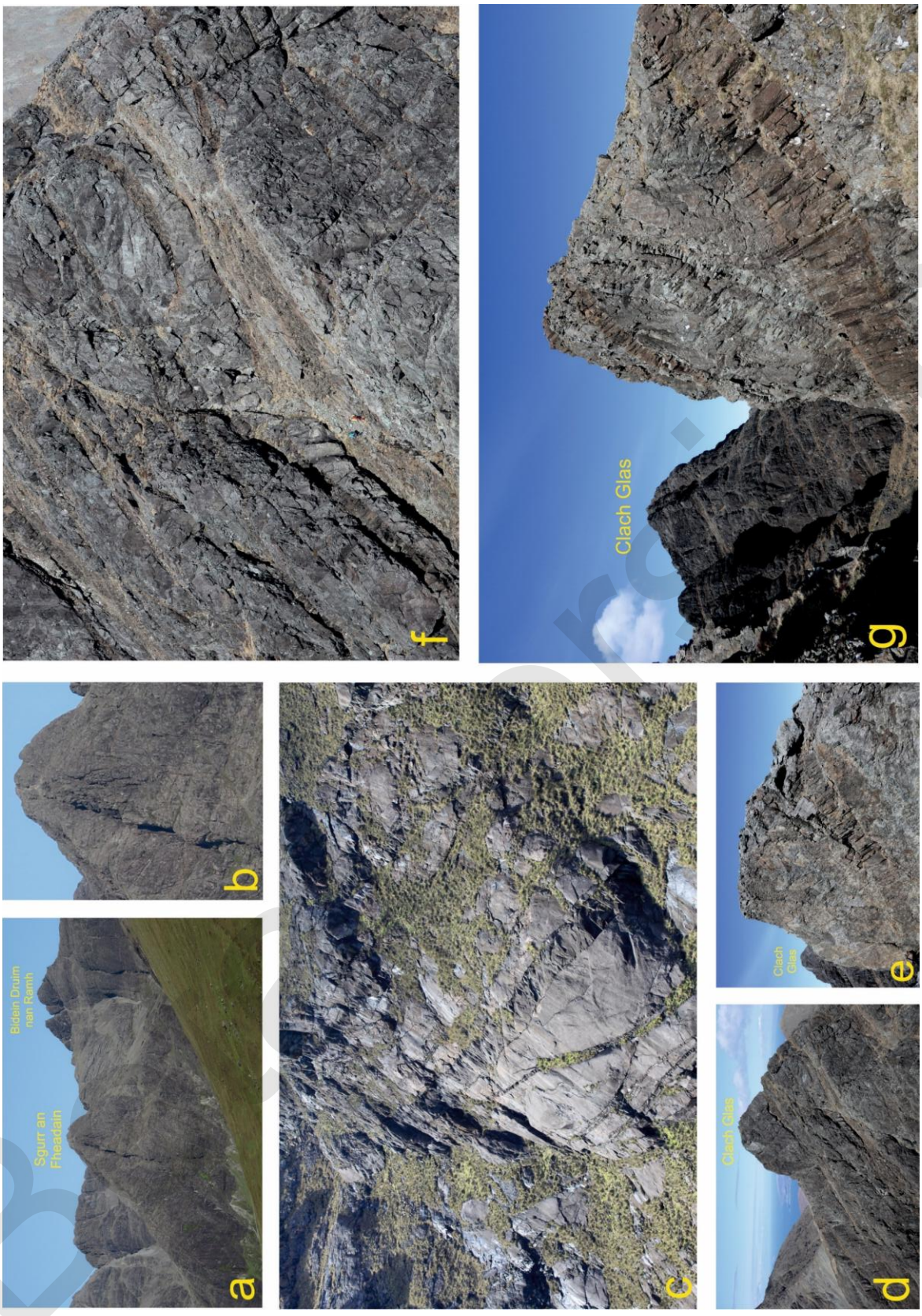


Figure 9-116: Basic (basalt and dolerite) cone-sheets and inclined sheets: (a) & (b), Sgùrr an Fheadain, NW Cuillin, Skye, a focus of cone-sheets and dykes; (c) – (f) examples of cone-sheets within the Cuillin Intrusive Centre ((c) between the Scavaig River and the Bad Step; (d), (e) & (g), east of Blà-Bheinn); (f) a detail of (d) with people for scale.

A second variety of cone-sheet is the porphyritic dolerite type, also free of olivine. Harker (1904) recorded their presence in Coire' a' Chruidh and east of Gars-bheinn, both in the southern part of the Cuillin. The phenocrysts within this type are zoned plagioclases, with compositions typical of the labradorite range, set in a groundmass of plagioclase, augite and Fe-Ti oxides. Locally, cone-sheets of this type contain phenocrysts of plagioclase up to 6 mm in length, with rounded margins, set in a granulitic groundmass of plagioclase, augite and Fe-Ti oxides.

Harker (1904) also identified a porphyritic olivine dolerite variety, which is restricted to the Sgùrr Thuilm area in the Western Cuillin. This type is relatively fine-grained and contains, in addition to olivine microphenocrysts, abundant phenocrysts of plagioclase.

A fourth type of cone-sheet identified by Harker (1904) is similar to the dominant non-porphyritic dolerite noted above, but is, in contrast, more basic and contains abundant groundmass olivine and bytownite. This mineralogical difference is readily noted in the field as these intrusions weather to a distinctive rusty-red. The rock which forms part of the twin summit area of Blà-bheinn is a particularly good example of this type of cone-sheet.

Bell *et al.* (1994) investigated the geochemical evolution of the cone-sheets from a suite of samples in a traverse between Rubha Bàn, south of Sgùrr na Stri, north to Sgùrr Hain. The most primitive samples are of tholeiitic basalt, almost identical in composition to that of the intracanyon lava of the Talisker Formation on Minginish (Chapter 6). Dykes from the axial zone of the Skye Main Dyke Swarm (Chapter 7) share the same compositional characteristics. Intra-suite compositional variation of the cone-sheets can be modelled in terms of low-pressure fractional crystallisation of olivine, clinopyroxene and plagioclase, with the most evolved composition(s) produced by 60% crystallisation of the most primitive composition. Trace-element and isotope geochemical data indicate that during fractional crystallisation of the cone-sheet magma(s), contamination by upper crustal country-rock material, most likely amphibolite facies gneisses of the Lewisian Gneiss Complex (Chapter 2) occurred (Chapter 10).

The cone-sheets pre-date most of the granites associated with the Skye Central Complex. However, cone-sheets do cut the Coire Uaigneich Granite (see below) and this led Richey (1932) to conclude that granites of (distinctly) different ages are present within the SCC.

9.7.6 Tholeiite sheets of the Western Cuillin

Within the gabbros (*s.l.*) of the Western Cuillin, several thick sheets of amygdaloidal tholeiitic basalt/dolerite and associated breccias are recognised by Hutchison (1966a). These rocks were originally described by Harker (1904), who concluded that they were remnants of the plateau lava sequence that had been incorporated into the gabbro by the foundering of large slabs into the magma chamber. Bailey (1952) re-investigated these rocks and suggested that they were normally crystallised, medium- to fine-grained tholeiitic basalt intrusions. This conclusion was also reached by Hutchison (1966a), and it is mainly from this work that the following descriptions are taken.

Two suites of intrusions are recognised (Figure 9-117): an Outer Complex, consisting of three near-horizontal, N-S -trending sheets west of Coire na Banachdich associated with many more inwardly-inclined (50–60°) sheets forming the lower parts of Coire na Banachdich; and, an Inner (Main Ridge) Complex, consisting of numerous sheets also dipping inwards at 60°, which crop out along the main Cuillin ridge (Figure 9-118; Figure 9-119).

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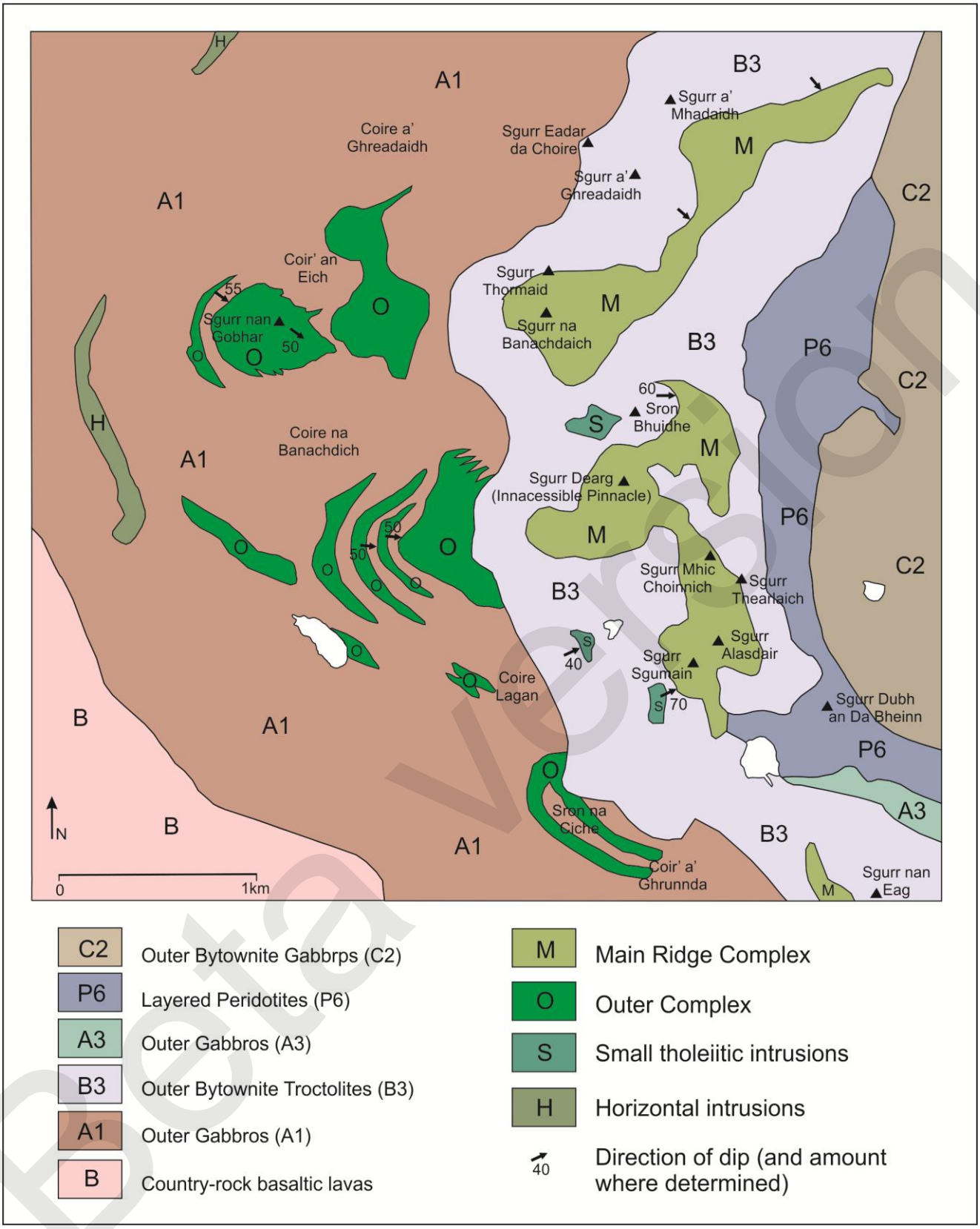


Figure 9-117: Simplified geological map illustrating the distribution of the Outer Complex and Inner (Main Ridge) Complex tholeiite sheets (after BGS 2005).

Within the Outer Complex, marginal facies of the sheets are either distinctly fine-grained, or show no decrease in grain-size. These sheets predominantly intrude the Outer Gabbros (A, see above). Xenoliths of local 'country-rock' intrusive rocks are common, and columnar joints have locally developed.

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Sheets belonging to the Inner Complex are intimately associated with various breccias, for example on Sgùrr Alasdair (Figure 9-118) and Sgùrr Sgumain, with tholeiitic basalt/dolerite acting as a matrix material. Hutchison (1966a) describes a diverse spectrum of rock-types, from 'welded' breccias (i.e. fragmental rocks with a coherent, crystalline basaltic matrix) to xenolithic intrusive basaltic rocks. These sheets intrude/cut rocks of the Border Group (B, see above) and the Outer Bytownite Troctolites (C, see above).



Figure 9-118: Tholeiite sheet of the Inner (Main Ridge) Complex on Sgùrr Alasdair. View towards the NE from near to Loch Coir' a' Ghrunnda.

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Figure 9-119: The Inaccessible Pinnacle, the true summit of Sgùrr Dearg on the Cuillin Ridge, formed predominantly of fragments of tholeiite sheets of the Inner (Main Ridge) Complex.

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The non-xenolithic portions of the tholeiite sheets range from coarse-grained dolerite through to fine-grained basalt, the latter rarely containing phenocrysts of plagioclase. The groundmass is typically composed of plagioclase and augite in an ophitic to sub-ophitic arrangement. Amygdales and interstitial patches of quartz and secondary hydrous silicates, such as chlorite and epidote, are also present.

Alteration of the 'country-rocks' by the Outer Complex tholeiite sheets is evidenced by the sericitisation of plagioclase feldspars and the schillerization of pyroxenes, together with the replacement of olivine and clinopyroxene by serpentine and a fibrous amphibole, respectively.

According to Hutchison (1966a), these tholeiitic basalt and dolerite sheets released volatiles during emplacement, causing brecciation and fragmentation of their host-rocks. Vesiculation occurred as the confining pressure reached critical (low) values. Subsequently, vesicles were infilled by secondary (amygdale) mineral assemblages. It is likely that, in terms of composition and mode of emplacement, there is a close connection between these tholeiite intrusions, the cone-sheets (see above) and the volcaniclastic pipes of the CIC (see above).

A myriad of thin, cross-cutting, basaltic sheets occur throughout the CIC, lacking the geometrical uniformity of the cone-sheets (see above), and are particularly well displayed on the Outer Bytownite Troctolite 'boiler plate' surfaces in Coir' a' Ghrunnda (Figure 9-120).

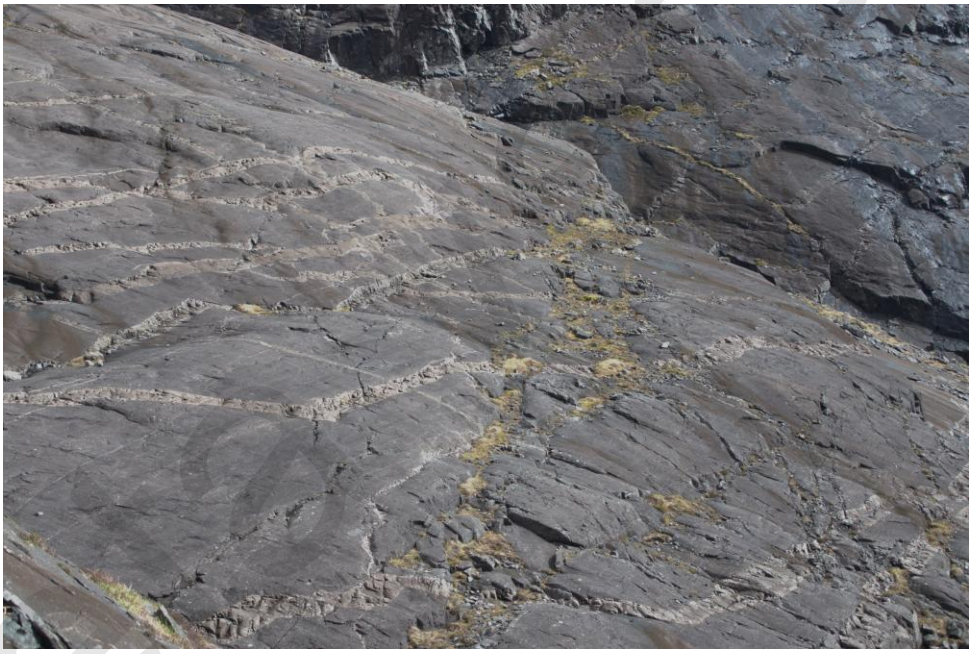


Figure 9-120: Thin, cross-cutting basaltic sheets within the 'boiler plates' in Coir' a' Ghrunnda (Outer Bytownite Troctolites).

9.7.7 The Coire Uaigneich Granite

The only rock of truly granitic composition associated with the CIC is the Coire Uaigneich Granite, which crops out along the SE margin of the intrusive centre, between Sgùrr na Stri and Coire Uaigneich (Figure 9-121), in a narrow, discontinuous, ribbon-shaped outcrop, and is most easily examined on the beach on the west side of the Abhainn Camas Fhionnairigh on the west side of Camasunary Bay, where it forms a wave-washed platform (Wager *et al.* 1953). On these clean surfaces, variations between coarse- and fine-grained facies are readily noted, as are partially digested xenoliths of sandstone (Figure 9-122; Figure 9-123). In hand-specimen, needles of hypersthene (typically replaced by bastite) are also conspicuous,

Be

in a pale granitic groundmass (Figure 9-123). SE of Sgùrr na Stri, the granite is intruded along the contact between Torridonian strata (Chapter 2) and metamorphosed basaltic lavas, and dips to the NW at an angle of between 35 and 50°. The only other place where the field relationships of the granite are easily examined is in Coire Uaigneich, itself, where it is intruded into Jurassic sedimentary rocks and basaltic lavas. Here, much of the outcrop is mantled by frost-shattered material.



Figure 9-121: Pale-weathered Coire Uaigneich Granite cropping out in the upper part of the Abhainn nan Leac valley on the east side of Blà-bheinn. The dark country-rocks on either side of the granite at the top of the valley are hornfelsed basaltic lavas. View towards NNE.



Figure 9-122: An elongate inclusion of fine-grained, metamorphosed sandstone, most likely derived from the Torridonian sequence that crops out in Camasunary Bay and the surrounding area, within typical Coire

Preview

Uaigneich Granite on the west side of the Abhainn Camas Fhionnairigh, where it flows into Camas Fhionnairigh. Pole *ca*. 1 m long.



Figure 9-123: Typical Coire Uaigneich Granite from the coastal exposures on the west side of the Abhainn Camas Fhionnairigh, where it flows into Camas Fhionnairigh. Original needles of hypersthene (now replaced by bastite, a variety of serpentine), set in a quartz-feldspar groundmass. The elongate, rounded inclusion is interpreted as being originally Torridonian sandstone. Coin *ca*. 26 mm across.

Near to its margins, fine-grained facies of the granite are locally developed, grading over a short distance into coarser material towards the interior of the intrusion. Interpretations of the age relationship between the granite and the main units of the CIC differ: Carr (1952) concluded that it predates the CIC, whereas Almond (1960) suggested that it formed at a later stage.

The presence of sandstone xenoliths within the Coire Uaigneich Granite lead Wager *et al*. (1953) to study the intrusion in more detail to determine if there is a genetic relationship. Within the granite, itself, they identified quartz paramorphs (pseudomorphs with the same composition), after tridymite, and suggested that the whole-rock composition of the intrusion falls within the primary quartz field of the synthetic system Qz-Ab-Or, when $P_{TOTAL} = P_{H2O}$ (= 1kbar). Consequently, they concluded that this granite represents a partial melt of Torridonian sandstone (see Chapter 2**,** and below). Experimental studies by Brown (1963) provided further evidence for this interpretation, suggesting that the melting events most likely took place at a depth of *ca*. 1 km.

Meighan (1976, 1979) proposed an alternative model, suggesting that the intrusion originated via fractional crystallisation of a basaltic magma, possibly associated with the CIC, and subsequently underwent silicification. Important to his arguments are significant differences in the major- and trace-

element chemistry between the granite and typical Torridonian sandstones from the surrounding area. Meighan (1976, 1979) also suggested that the so-called paramorphs of quartz, after tridymite, are the hydrothermal replacement of plagioclase by quartz.

Dickin & Exley (1981) investigated the major-, trace- and isotope-element characteristics of the intrusion and concluded that it has not undergone any significant change in bulk composition since its crystallisation, for example by reaction with hydrothermal fluids, and that it formed by the mixing of two distinct magmas: one being a partial melt of Torridonian sedimentary material, the other a silicic differentiate of a basaltic magma (from a Cuillin magma chamber) enriched in incompatible elements such as Zr and Y. According to their data modelling, the mixing involved two parts of Torridonian melt for every part of the basaltic differentiate.

9.7.8 Thermal and metasomatic effects

Ferry (1985a) investigated the nature of hydrothermal reactions within the gabbroic rocks of the Cuillin Intrusive Centre. The primary igneous assemblage - olivine, augite, hypersthene, plagioclase, magnetite, and ilmenite - was variably overprinted by hydrous mineral parageneses reflecting progressive fluid ('water')-rock interaction. The most pervasive secondary phases include talc, chlorite, smectitic clays, calcic amphibole, biotite, and magnetite; less abundant alteration products comprise epidote, calcite, quartz, titanite, prehnite, and garnet. These assemblages delineate reaction pathways that systematically replaced anhydrous ferromagnesian silicates with hydrous sheet and framework silicates, stabilized oxides, and precipitated late carbonates.

Whole-rock geochemical data demonstrate that alteration was accompanied by selective elemental mobility. Potassium, sodium, strontium, and 'water' were consistently gained, while magnesium was lost, implying metasomatic introduction of alkalis and removal of Mg to the fluid phase. Aluminium and calcium concentrations remained largely unchanged, indicating conservation of major rock-forming components despite mineralogical transformation. Iron and silica behaved in a non-monotonic fashion: early stages of alteration were characterized by iron oxidation and silica leaching, whereas later stages saw iron reduction and silica re-enrichment. These contrasting trends record dynamic shifts in fluid composition and redox state during the lifetime of the hydrothermal system.

Quantitative progress of alteration reactions - particularly the conversion of olivine to talc + magnetite at *ca*. 525–550 °C indicates fluid/rock ratios of 0.2–6 (volume basis). In contrast, isotopic fluid/rock ratios are higher, *ca*. 1–10, reflecting that isotopic exchange occurred earlier and at higher temperatures than mineralogical alteration. This disparity corroborates a decoupled temporal sequence between isotopic modification and mineralogical transformation.

Collectively, these lines of evidence support a model of pervasive fluid infiltration through crystalline gabbro at *ca*. 500 °C, leading to significant, temperature-dependent mass transfer, isotopic exchange, and mineralogical overprinting. The sequence spans from high-temperature isotopic equilibration (>550 °C), through mineralogical alteration (*ca*. 450–550 °C), to late-stage, cooler mineral precipitation (<300 °C).

In terms of processes as temperatures decreased: (a) the magmatic stage (1000–1150 °C) when primary minerals crystallize, with pyroxene resistant to later modification; (b) high-T isotopic exchange (>550 °C), when fluid infiltration initiates isotopic equilibration without mineral overprint; (c) mineralogical alteration (450–550 °C), when chemical and textural transformation of olivine occurs, with strong element mobility;

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and, (d) late-stage alteration (<300 °C), when the secondary mineral assemblage grows to include epidote, prehnite, and carbonates in cooler, waning fluid flow.

9.8 Red Hills granite intrusive centres

9.8.1 Introduction

Granites form the Red Hills of Skye, which extend from Glen Sligachan to Strath, near Broadford. There are three distinct intrusive centres; from oldest to youngest they are the Srath na Crèitheach, Western Red Hills and Eastern Red Hills centres. Each centre contains several discrete intrusions, varying from steep-sided bosses through to segments of ring-intrusions. Field relationships suggest that certain of the intrusions are true ring-dykes, where space was made available by central subsidence of a block of older country-rocks (which may in part have comprised older granites), but this style of intrusion is by no means ubiquitous. More commonly, the outcrop patterns of the granites suggest broad, curved, dyke-like masses. Emplacement of the granites does not appear to have resulted in appreciable disturbance of the earlier rocks. Stoping and brecciation of the country-rocks is generally absent, although there may be peripheral folding of country-rocks on the northern slopes of Glamaig and in the vicinity of the Beinn an Dubhaich Granite.

Evidence for volcanic activity, possibly from calderas that developed because of central subsidence, is at best circumstantial. Silicic pyroclastic rocks are preserved locally, for example within the sequences of volcaniclastic deposits in the Kilchrist area of Strath (see below). In addition, within the offshore sedimentary basins of the North Sea and west of the Shetland Isles, thin beds of silicic pyroclastic rocks are intercalated with marine sedimentary rocks of Paleocene age and are considered to have been derived from the volcanic centres of either the Hebridean Igneous Province or even East Greenland (e.g. Knox & Morton 1988).

9.8.2 The Srath na Crèitheach Intrusive Centre (SnCIC)

9.8.2.1 Introduction

The Srath na Crèitheach Intrusive Centre (SnCIC) (Figure 9-124) is defined here as a group of three sub-volcanic granitic intrusions, the Meall Dearg, Ruadh Stac and Blaven (Blà-bheinn) granites, which post-date the Cuillin Intrusive Centre (see above) and pre-date the Western Red Hills Intrusive Centre (see below). These intrusions, covering an area of *ca*. 7 km^2, crop out in Srath na Crèitheach, on the hills of Meall Dearg and Ruadh Stac, and on part of the west side of Blà-bheinn (Figure 9-125). The older, spatially associated, volcaniclastic rocks that crop out to the south and west of the granites are discussed in Chapter 6.

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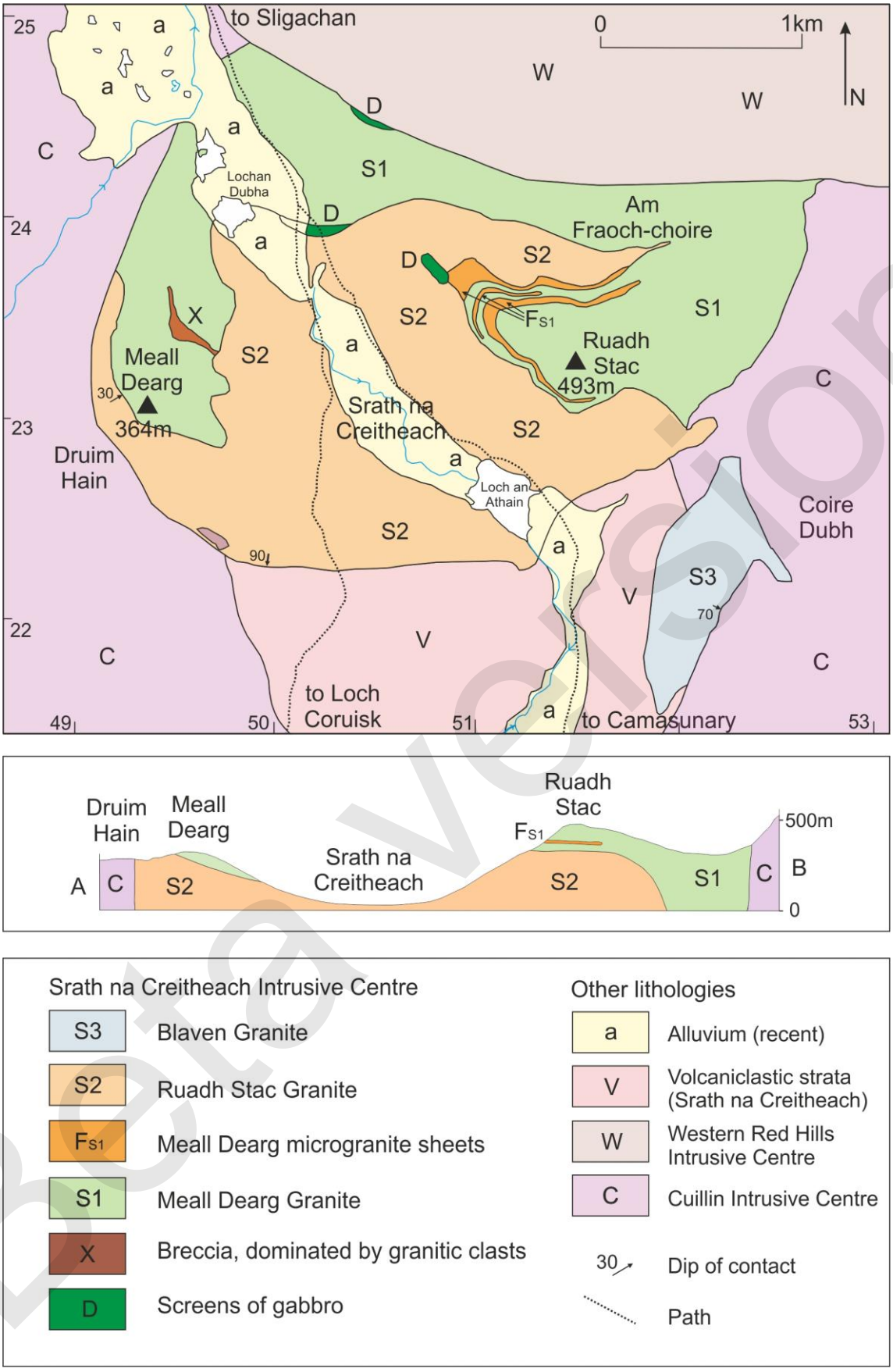


Figure 9-124: Lithodemic units of the Srath na Crèitheach Intrusive Centre (SnCIC) (based on BGS (2005) and Emeleus & Bell 2005).

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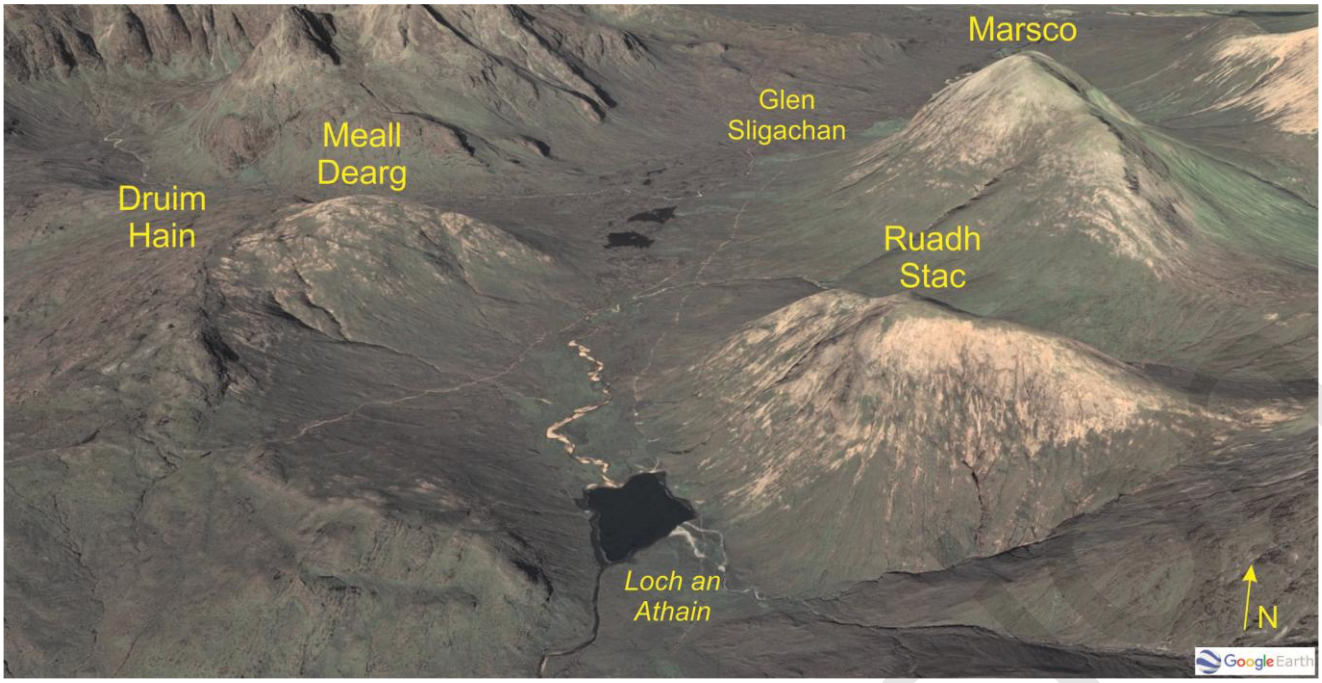


Figure 9-125: Oblique Google Earth© image of the Srath na Crèitheach Intrusive Centre (SnCIC) area, with Ruadh Stac in the near ground, separated from Meall Dearg in the distance by the glacially excavated valley of Srath na Crèitheach. View towards the north.

Very little published data are available on these granite intrusions. Geikie (1894), in a discussion of the time-relationships between the Cuillin gabbros (*s.l.*) and the granites of the Red Hills, provides evidence that the former pre-date the latter. He also notes that riebeckite is present within one of the granites exposed on Meall Dearg. The conclusions of Geikie are amplified by Harker (1904), who also delineates the outcrop of the 'riebeckite-bearing granophyre' on his unpublished 6 inch to 1 mile map. Anwar (1950, 1955) presents an analysis of a clinopyroxene (ferrohedenbergite) from the other granite exposed on Meall Dearg (see below). Thompson (1969) examined the granites of the Srath na Crèitheach area and concluded that they define an older intrusive centre that is distinct from the Western Red Hills Intrusive Centre further north. He also concludes that two intrusions may be defined, referring to them as the Meall Dearg and Ruadh Stac granites. According to Thompson (1969), the dome-shaped Ruadh Stac Granite lies below the Meall Dearg Granite and pre-dates the latter. However, Jassim (1970) concludes that the reverse time-relationships can be discerned, with the Ruadh Stac Granite chilling against, and hence post-dating, the Meall Dearg Granite.

The descriptions presented below draw partly upon the studies of Thompson (1965, 1969) and Jassim (1970).

9.8.2.2 General field relationships

The three granites of the SnCIC post-date the basic and ultrabasic rocks of the Cuillin Intrusive Centre (CIC) (Figure 9-124; Figure 9-125; Figure 9-126; Figure 9-127). Typically, contacts are steep, or vertical, with the development of marginal chill facies, locally containing spherulitic aggregates involving quartz and alkali feldspar. Apophyses (offshoots) of the granite intrusions invade the surrounding gabbros (Figure 9-126). These two features are particularly well developed at the margin of the Ruadh Stac Granite, south of the summit of Meall Dearg, at Druim Hain (Harker 1904). Accordingly, the older gabbros are intensely altered over distances of 10–40 m from the granite contact. The plagioclases are opaque and distinctly white, whereas the pyroxenes take on a greenish tinge, with the development of secondary chlorite and

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epidote. Xenoliths of altered gabbro are common within the marginal facies of the Blaven Granite, are less common in the Ruadh Stac Granite, and are absent from the Meall Dearg Granite.

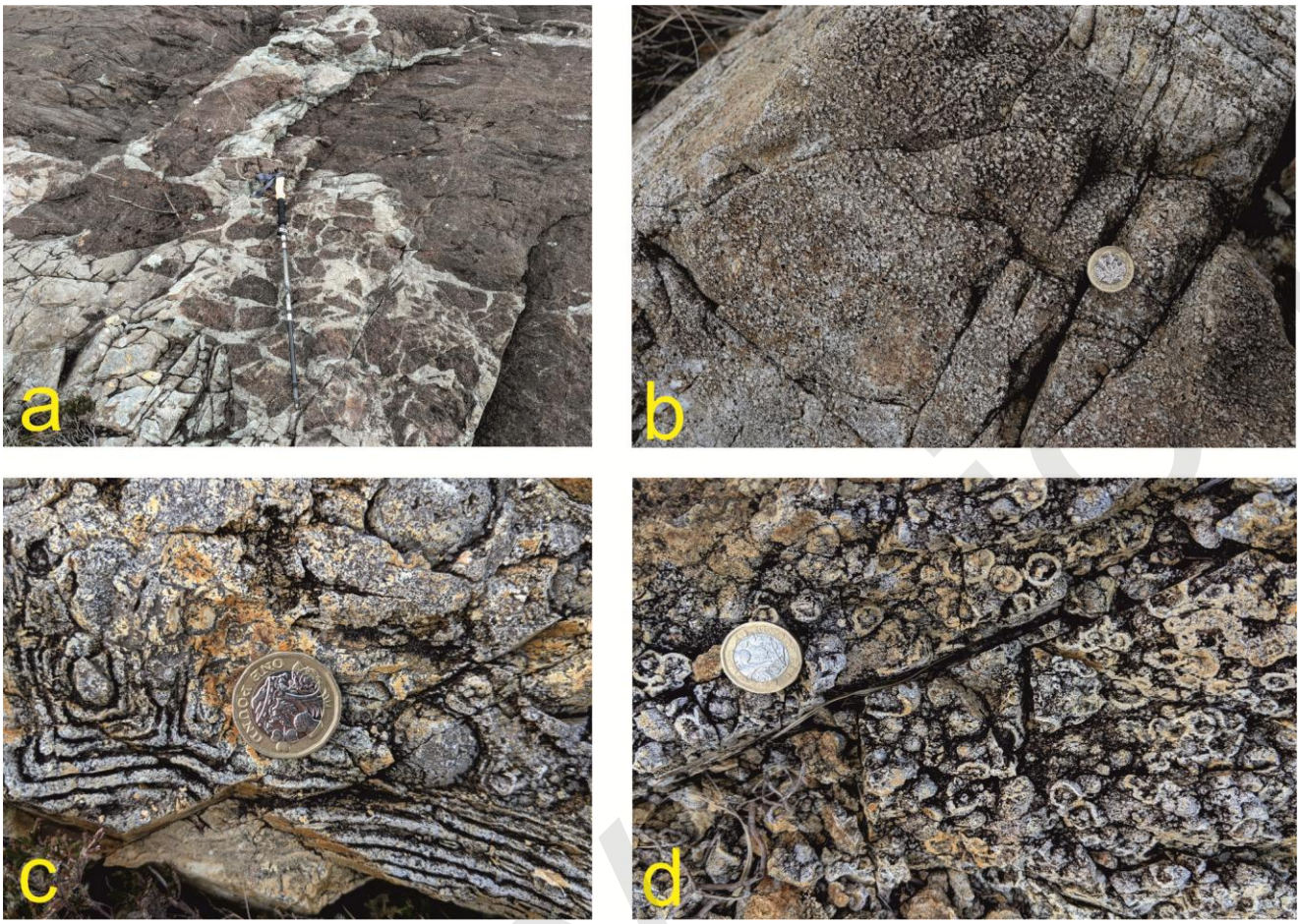


Figure 9-126: (a) Pale rhyolitic apophysis of the Ruadh Stac Granite within Inner Layered Gabbros (F), with fragments of disrupted gabbro, on Druim Hain, pole *ca.* 1 m long; (b) spherulitic aggregates within an apophysis of the Ruadh Stac Granite, coin *ca.* 24 mm across; (c) detail of banded rhyolite within an apophysis of the Ruadh Stac Granite, coin *ca.* 24 mm across; and, (d) detail of spherulitic aggregates within an apophysis of the Ruadh Stac Granite, coin *ca.* 24 mm across.

The boundary between the Srath na Crèitheach and Western Red Hills intrusive centres runs along the southern face of Marsco at approximately 300 m OD and is concave to the north. Along part of the contact a screen of crushed gabbro, approximately 400 m long, separates the granites of the two centres. It is likely that this material was originally part of the Inner Gabbros, subsequently caught up in the younger granites.

Botav



Figure 9-127: Margin of the Srath na Crèitheach Intrusive Centre against the older Cuillin Intrusive Centre along the northern side of the ridge of Druim Hain.

The older volcaniclastic rocks, in the immediate vicinity of the granites, have been subjected to intense brecciation and alteration. The various components of the sequence within this crush zone have reacted differently, with fine-grained, fragmental material having the greatest degree of alteration. Marginal rhyolitic veins are common, cutting the volcaniclastic rocks and resulting in their alteration. This type of alteration is particularly well-developed SW of Loch an Athain, where there is a 50 m-wide zone consisting of fine-grained fragments of basic and ultrabasic material surrounded by large patches of quartz and alkali feldspar in a granophyric intergrowth, together with abundant plagioclase and hornblende.

9.8.2.3 The Meall Dearg Granite

The Meall Dearg Granite crops out on the upper slopes of Meall Dearg and Ruadh Stac and is most easily examined on Ruadh Stac, where it clearly overlies the Ruadh Stac Granite (Figure 9-124; Figure 9-128). In general, the sheet-like Meall Dearg Granite dips to the east at an angle of *ca.* 30°. It may be identified in the field by its whitish-brown coloration on weathered surfaces, whereas when fresh it has a pale green tinge. Two facies of the granite are recognised, occurring as interleaved sheets. These are: a fine-grained, hornblende-bearing granite; and, a younger, coarse-grained, pyroxene-bearing granophyre. The contact relationships between these closely associated, flat-lying sheets are most readily observed on the northern slopes of Ruadh Stac, when viewed from Marsco.

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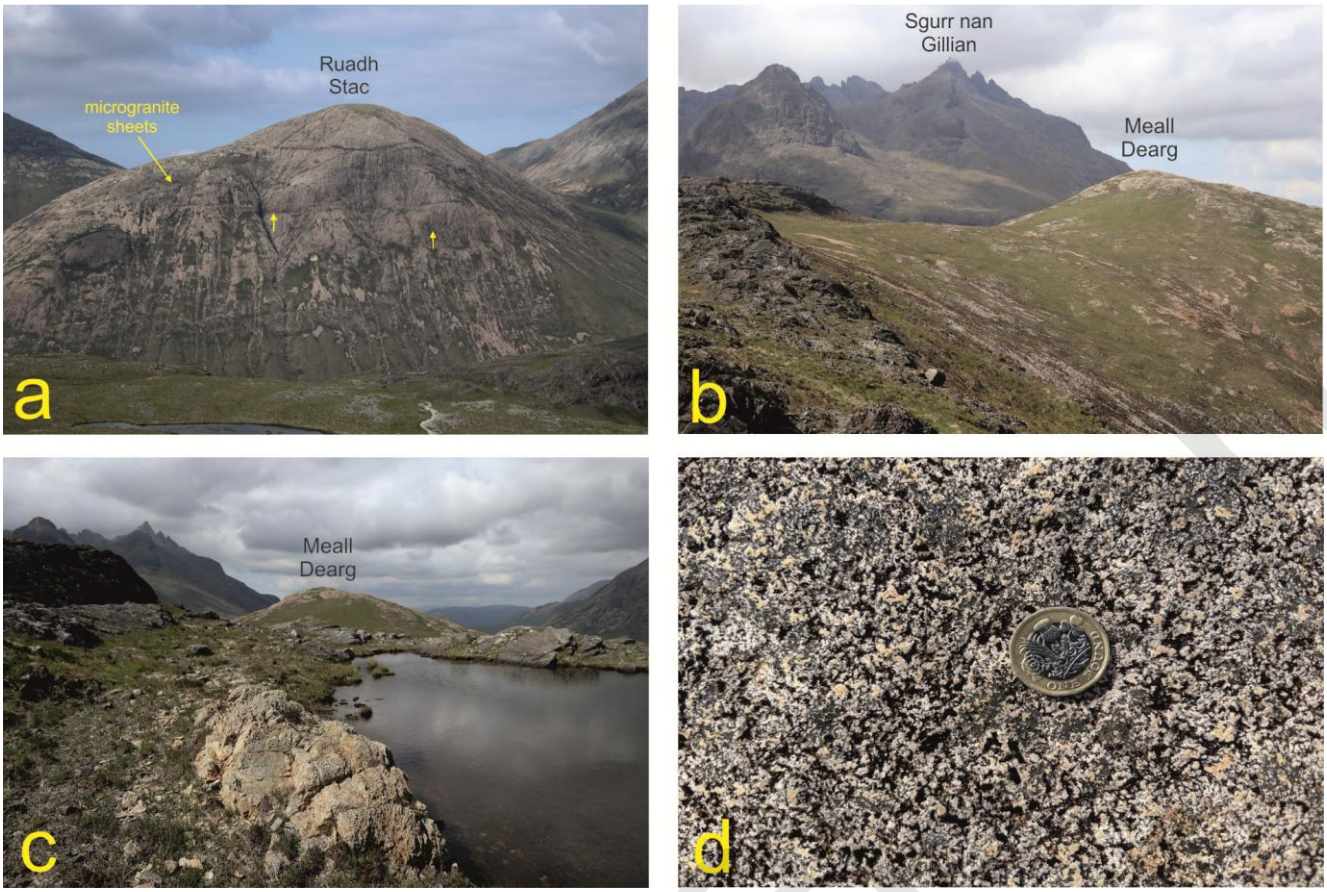


Figure 9-128: (a) Ruadh Stac viewed towards the ESE from Druim Hain, with the younger Ruadh Stac Granite below the (older) Meall Dearg Granite, with a relatively horizontal contact (arrowed); (b) contact of pale Meall Dearg Granite with dark, older Inner Gabbros on Druim Hain; (c) pale dyke-like offshoot of the Ruadh Stac Granite within Inner Gabbros on Druim Hain, with dome-shaped Meall Dearg in the middle distance; and, (d) typical medium-grained Meall Dearg Granite, coin *ca.* 24 mm across.

In detail, the hornblende-bearing variety, exposed halfway up the northern face of Ruadh Stac, consists of three distinct sheets. These sheets dip at a very shallow angle to the NE and are between 5 and 30 m thick. The rock is aplitic, containing large needles of hornblende. Quartz dominates the rock, constituting up to 40% of the mode, together with approximately 10% of plagioclase-cored alkali feldspar phenocrysts, giving the rock a porphyritic appearance. Xenoliths of gabbro and granite are present in various stages of assimilation.

The pyroxene-bearing variety of the Meall Dearg Granite has a much coarser appearance and forms three sheets. The pyroxene is ferrohedenbergite, which occurs in association with Fe-rich olivine, fayalite (typically altered to chlorite + haematite). The groundmass is dominated by quartz and alkali feldspar in a granophyric intergrowth. These sheets have weathered more deeply than the hornblende-bearing variety and have a slightly paler/lighter appearance.

Although texturally distinct, the bulk mineralogies of the two varieties of the Meall Dearg Granite are very similar. The differences in the mafic mineral assemblages within the two facies are most easily attributed to differences in the relative H_2O contents of the magmas during crystallisation. Thompson (1965) reported the presence of fluorite as an abundant accessory mineral in both facies of the Meall Dearg Granite.

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9.8.2.4 The Ruadh Stac Granite

The Ruadh Stac Granite has previously been referred to as the 'Riebeckite Granophyre' (Geikie 1894; Anwar 1955), although subsequent investigations (Thompson 1965, 1969, 1976) indicate that the compositional range of the amphiboles is broader, from arfvedsonite to ferrorichterite.

This intrusion weathers, commonly deeply, to a pale brown, and underlies the Meall Dearg Granite (Figure 9-124; Figure 9-128), with intervening slabs of gabbro present along the contact (see below). It crops out on both Ruadh Stac and Meall Dearg, up to a height of *ca*. 300 m OD. Its base is not exposed. Fresh material is most readily examined in the stream beds of the Allt nam Fraoch-choire and the Allt Teanga Bradan, north and south of Ruadh Stac, respectively.

The textures present within this granite are extremely variable, from aplitic, through porphyritic, to granophyric. Sparse phenocrysts are of subhedral perthite and amphibole constitutes *ca*. 5% of the rock.

9.8.2.5 The contact between the Meall Dearg and Ruadh Stac granites

Although uncertainty surrounds the time-relationships of these two granites, some field-relationships are not in dispute. First, the junction is readily identified because of the distinctly different weathering characteristics of the two intrusions; the Meall Dearg Granite has a rugged, irregular appearance, whereas the Ruadh Stac Granite is darker, more fractured, and weathers to much smoother surfaces (Figure 9-124; Figure 9-128). Second, gabbro slabs are locally present along the contact between the two intrusions.

A 'needle-sharp' contact just above the gabbro slabs on the NW slopes of Ruadh Stac indicated to Jassim (1970) that the Ruadh Stac Granite chilled against the Meall Dearg Granite. Thompson (1965, 1969) concluded the reverse relationship.

9.8.2.6 The Meall Dearg Breccias

On Meall Dearg, various breccias occur within the Meall Dearg Granite. They are considered by Jassim (1970) to be the result of volatile release closely associated with the incoming of the Ruadh Stac Granite. The main exposures are located *ca*. 400 m NE of the summit of Meall Dearg, trending NW-SE, with a width of 50–100 m and a length of 300 m, tapering at both ends into narrow dyke-like masses. The main upper part of this outcrop of breccia comprises relatively coarse-grained material, with blocks of conspicuously spherulitic-textured granite, which contrast with the finer-grained material with associated crush zones lower down on Meall Dearg. The fragments are readily identified as being ferrohedenbergite-bearing granite of the Meall Dearg intrusion (see above).

Related to these rocks are numerous breccia dykes, generally less than 1 m wide, which are common within the Meall Dearg Granite, but only rarely seen within the Ruadh Stac Granite. Inclusions in these dykes are similar to those in the breccias described above, set in a matrix of comminuted rhyolitic material.

9.8.2.7 The Blaven (Blà Bheinn) Granite

The Blaven Granite crops out on the lower, western slopes of Blà-bheinn (Blaven), from the northern end of Loch na Crèitheach, north to Coire Dubh (Figure 9-129). On its east side, the granite is in contact with rocks of the Outer Bytownite Gabbros, whereas to the west it intrudes various volcaniclastic rocks (see above). Both contacts are steep, dipping to the NE.

Beta version



Figure 9-129: The Blaven (Blà Bheinn) Granite, intruded into Outer Bytownite Gabbros above (west side of Blà Bheinn). View towards the NE from Druim Hain.

A marginal facies of finer-grained material is commonly present, up to 10 m wide. Along the granite-gabbro contact, numerous elongate slabs of extremely altered gabbro are present within the granite.

The intrusion is generally pale when fresh, of medium grain-size (1–2 mm) and contains phenocrysts of alkali feldspar. The dominant mafic mineral is a green hornblende, typically altered to chlorite, which occurs in irregularly shaped clots.

9.8.2.8 The shapes and mechanism of intrusion of the granites

From the studies of Thompson (1965) and Jassim (1970), the Ruadh Stac Granite is dome-shaped and underlies the sheet-like Meall Dearg Granite. According to Jassim (1970), the Meall Dearg Granite has an 'inverted L' shape, forming an incomplete ring-dyke, with the steep limb located east of the summit of Ruadh Stac, against the Outer Bytownite Gabbros (see above), and the flat-lying roof-rocks exposed on the summits of Ruadh Stac and Meall Dearg (Figure 9-124; Figure 9-128). The presence of two varieties of the Meall Dearg Granite (see above) indicates multiple injections of magma.

The almost-vertical, sheet-like shape of the Blaven Granite suggests that the level of erosion is deeper for this intrusion, when compared to the other granites of the SnCIC, with the outcrop pattern possibly being that of the limb of a very incomplete ring-dyke, or simply a dome-shaped intrusion.

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9.8.3 The Western Red Hills Intrusive Centre (WRHIC)

9.8.3.1 Introduction

The Western Red Hills Intrusive Centre (WRHIC) (Figure 9-130; Figure 9-131) was first defined as a distinct intrusive centre by Richey (1932), when he distinguished the granites of the Glamaig-Marsco-Loch Ainort area from the younger Eastern Red Hills Intrusive Centre, west of Broadford (see below). The intrusive centre covers an area of *ca*. 35 km^2 and, at the present level of erosion, is dominated by annular silicic intrusions of granite, granophyre and felsite/rhyolite. Significantly, one of the earliest members of the centre is the Marsco Summit Gabbro, constituting the only true basic intrusion. One other important feature of the centre is the presence of a group of rocks referred to as the Marscoite Suite, consisting of a narrow composite ring-dyke, comprising (units of) ferrodiorite (an Fe-enriched fractionate of a tholeiitic basalt magma), a felsite (the Southern Porphyritic Felsite/Rhyolite) and various hybrid rocks ('marscoite' and 'glamaigite'), which were formed by magma mingling/mixing processes.

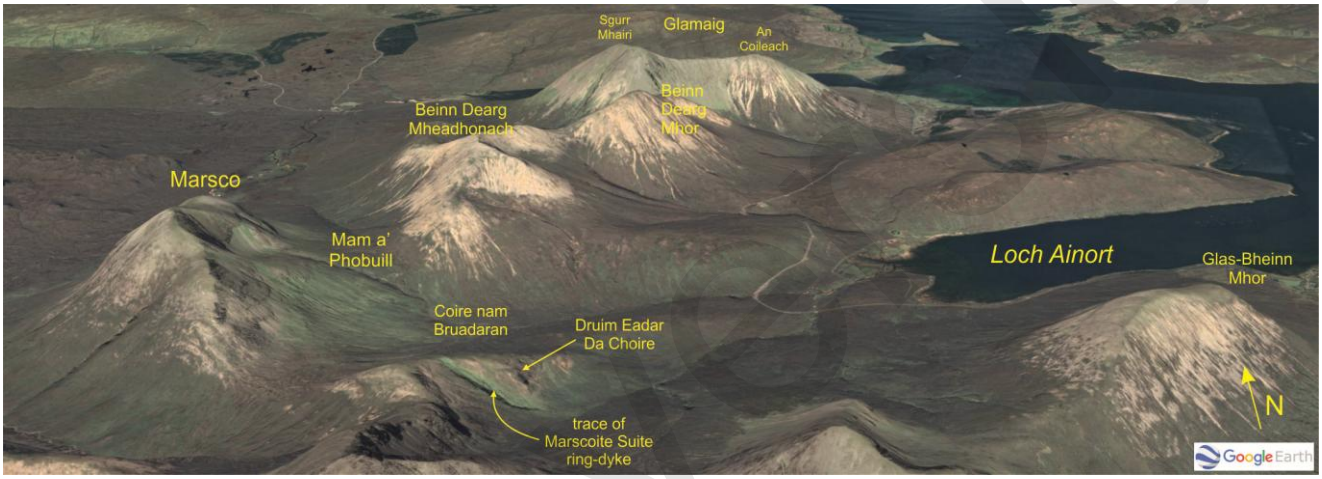


Figure 9-130: Oblique Google Earth© image of the Western Red Hills Intrusive Centre (WRHIC) area. View towards the north.

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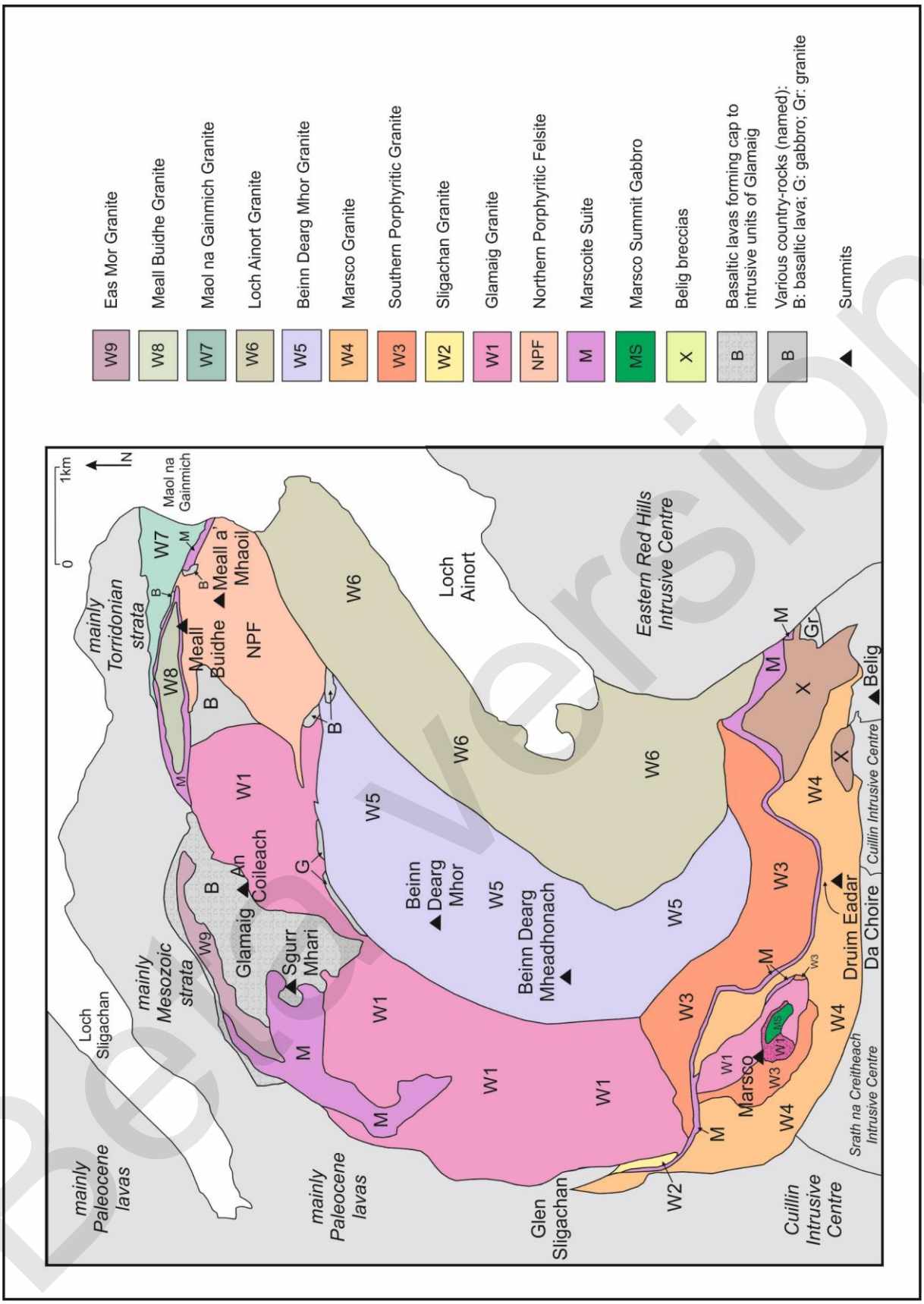


Figure 9-131: Lithodemic units of the Western Red Hills Intrusive Centre (WRHIC) (based on Emeleus & Bell 2005).

Review version

A detailed investigation of the rocks of the Western Red Hills Centre was undertaken by Wager and his co-workers, commencing with a preliminary report by Richey *et al.* (1946) that discusses age relationships between the granites. The results of this investigation are presented by Wager & Vincent (1962), Wager *et al.* (1965), Bell (1959, 1966) and Thompson (1965, 1969). Subsequently, Thompson (1980) suggested that aspects of the petrology of the granites, as well as the Marscoite Suite, may be explained in terms of magma mingling/mixing processes throughout the development of the intrusive centre.

A summary of events comprises:

INTRUSIVE EVENTS	**PRINCIPAL ROCK-TYPE(S)**
[YOUNGEST]	
dykes	dolerite, vitrophyre ('pitchstone'), aplite
Marsco Granite	plagioclase porphyritic fayalite ferrohedenbergite granite/granophyre
Meall Buidhe Granite	plagioclase porphyritic ferrohedenbergite amphibole microgranite
Northern Porphyritic Felsite	quartz-alkali feldspar porphyritic felsite
Marscoite Suite	marscoite, ferrodiorite, glamaigite, felsite/rhyolite, andesinite
Southern Porphyritic Granite	quartz-alkali feldspar porphyritic felsite/ microgranite/granophyre
Glen Sligachan Granite	alkali feldspar porphyritic fayalite microgranite
Loch Ainort Granite	alkali feldspar porphyritic fayalite ferrodedenbergite granophyre
Beinn Dearg Mhòr Granite	alkali feldspar porphyritic fayalite ferrodedenbergite granophyre
Eas Mòr Granite	alkali feldspar porphyritic amphibole granophyre
Maol na Gainmhich Granite	arfvedsonite granite
Glamaig Granite	plagioclase porphyritic hastingsite biotite granite/granophyre
Marsco Summit Gabbro	(olivine) gabbro (altered)
[OLDEST]	

9.8.3.2 The Marsco Summit Gabbro (MS)

The Marsco Summit Gabbro forms a distinct cap to the SE part of the summit of Marsco (Thompson 1969) (Figure 9-132; Figure 9-133). It crops out as a relatively flat-lying sheet and is underlain by the Glamaig Granite, the first of the WRHIC granite intrusions (see below). Numerous veins of rhyolite from the Glamaig Granite have intruded and fragmented the gabbro, giving rise to zone of stoping several metres wide. In this zone, the gabbro is typically brecciated and metamorphosed, although in places there is a sharp, locally crenulate boundary.

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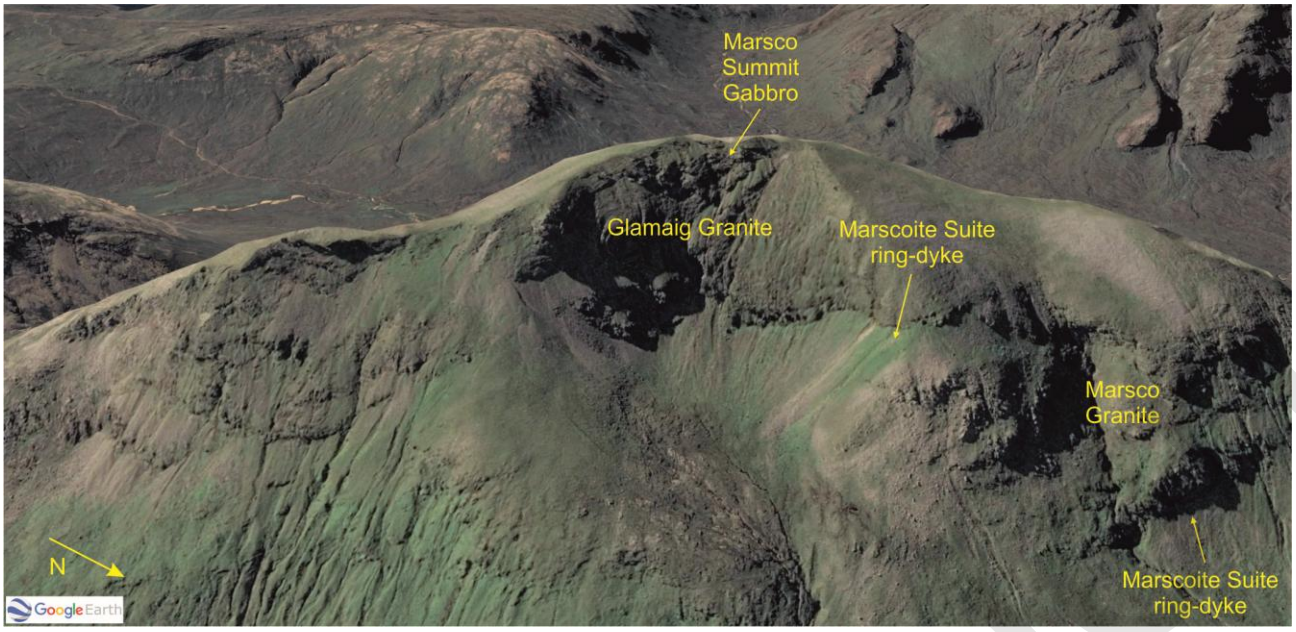


Figure 9-132: Oblique Google Earth© image of the summit area of Marsco, indicating the outcrop of the Marsco Summit Gabbro. View towards the SW.



Figure 9-133: Exposures of the Marsco Summit Gabbro. View towards the SE.

The gabbro has a distinct brown coloration and, unlike the gabbros of the CIC, is not intruded by cone-sheets (see above). It is composed of clinopyroxene and plagioclase (with cores of $An_{67–74}$, zoned to rims

of An_{50}, (Thompson 1965), in an ophitic arrangement. Olivine is not common and is typically altered. Thompson (1965) also reported the presence of orthopyroxene, Fe-Ti oxides, apatite and zircon, together with interstitial hornblende and biotite.

The presence of a fine-grained, marginal facies to this sheet, with sub-variolitic textures involving skeletal plagioclase phenocrysts, suggests that intense chilling of the basic magma occurred locally. This chilling, together with patches of coarse-grained gabbro that are fragmented by the Glamaig Granite, lead Thompson (1969) to conclude that prior to, and during, the intrusion of the granite, the Marsco Summit Gabbro was partly crystalline, but with pockets of melt still present.

9.8.3.3 The Glamaig Granite (W1)

The medium-grained, amphibole- and biotite-bearing granite that crops out over a broad tract of ground, *ca*. 9 km^2, running from Glamaig in the north, to Marsco in the south (Figure 9-130; Figure 9-131), was originally referred to as G1 by Richey *et al*. (1946) and Wager *et al*. (1948) but subsequently renamed the Glamaig Granite by Wager *et al*. (1965). The outer margin has the development of extensive crush planes within a porphyritic felsite chill facies and is thought to be vertical, as is the inner contact with the later/younger Beinn Dearg Mhòr Granite (Figure 9-134) (see below). The normal, coarse-grained granite weathers to a dull grey, contains miarolitic cavities, and is characterised in the field by the presence of small, rounded to sub-angular, mafic inclusions (5–50 mm) (Figure 9-135). These inclusions constitute up to 5 vol. % of the rock and are relatively evenly distributed throughout its mass. Typically, the larger inclusions have distinct outlines, whereas the smaller ones have less clearly defined margins and appear simply as clots or aggregates of mafic minerals. Also present are leucocratic inclusions of fine-grained material, up to 4 m across, typically found within the central part of the intrusion.

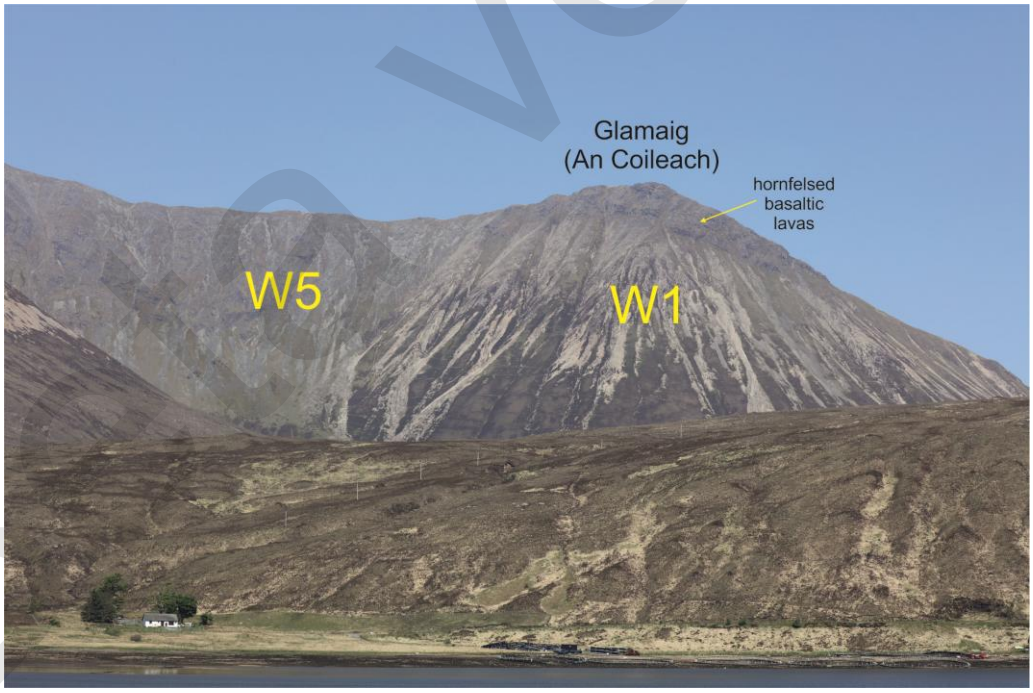


Figure 9-134: The near-vertical contact between the Glamaig (W1, right-hand-side) and Beinn Dearg Mhòr (W5, left-hand-side) granites. A cap of hornfelsed country-rock basaltic lavas forms the summit of Glamaig (An Coileach) and dips top-left to bottom-right. View is towards the west across Loch Ainort to the Beinn Dearg Mhòr - Glamaig ridge.

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Figure 9-135: Typical mafic inclusions (e.g. top, left of centre) within the Glamaig Granite in exposures in the Allt na Measarroch. Coin *ca.* 24 mm across.

In the Marsco area, the Glamaig Granite is overlain by the younger Southern Porphyritic Granite on the north side of the mountain. On the south side of Marsco this relationship is reversed and the Glamaig Granite is overlain by the Marsco Summit Gabbro (Figure 9-136).

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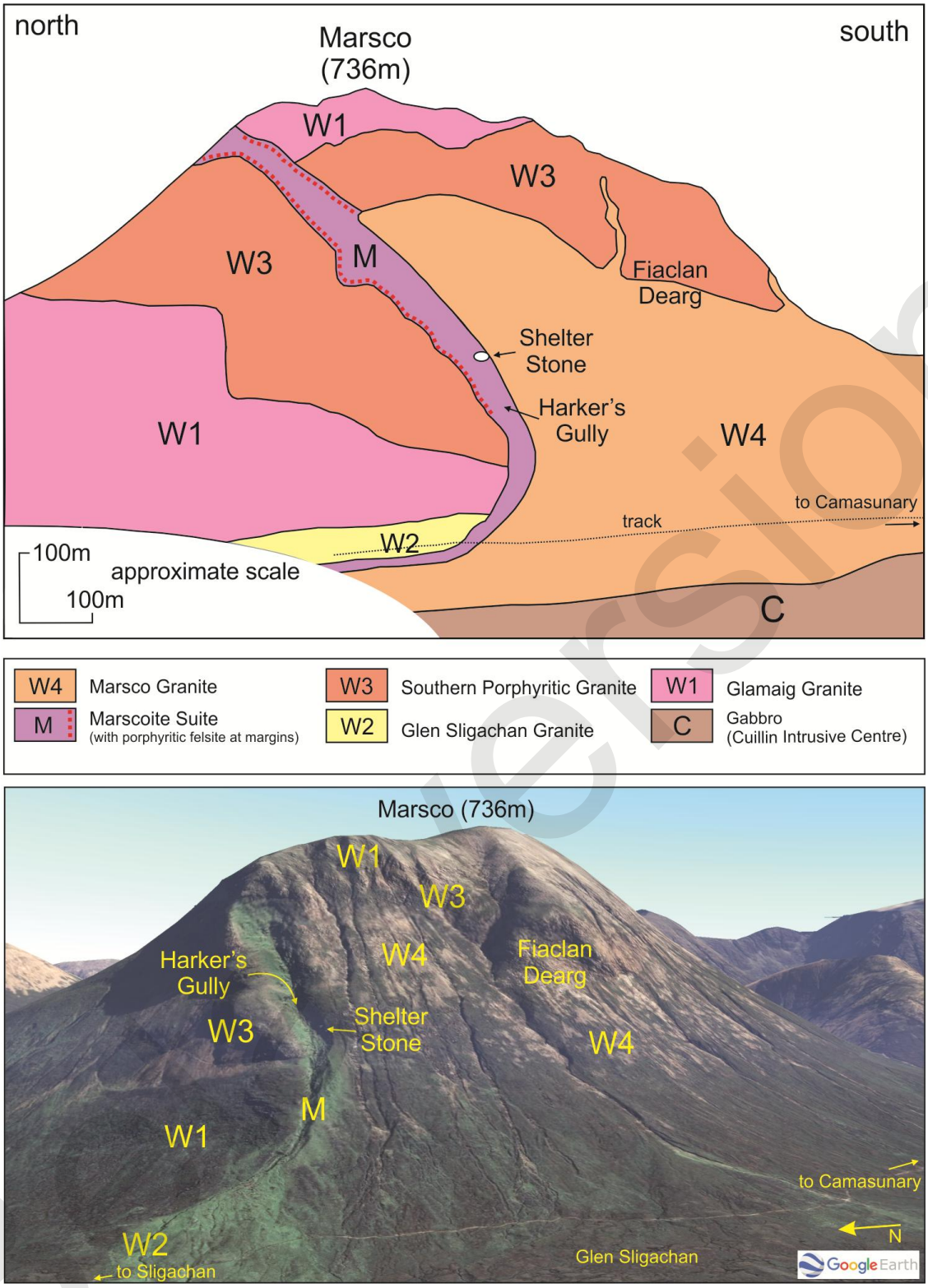


Figure 9-136: Oblique Google Earth© image and schematic figure of the west side of Marsco illustrating the field relationships of the various granites and the Marscoite Suite Ring-dyke. View is towards the east.

In detail, the Glamaig Granite is dominated by equigranular quartz, alkali feldspar and plagioclase (2–8 mm), together with small quantities of calciferous amphibole (hastingsite), clinopyroxene, biotite, Fe-Ti oxides and various other accessory minerals (Thompson 1969). Thompson (1980) suggested that the mafic inclusions dispersed throughout the volume of this granite were introduced in the form of basic magma, which was injected into the base of a magma chamber dominated by Glamaig-type silicic

Preview version

magma. One consequence of this interaction would be the net transfer of heat from the hotter basic magma into the cooler silicic magma, causing the latter to convect and further entrain the former.

9.8.3.4 The Maol na Gainmhich and Eas Mòr Granites (W7 & W9)

The Maol na Gainmhich and Eas Mòr granites were identified by Wager *et al.* 1965) as having formed early in the evolution of the WRHIC. However, no direct evidence of their age(s) relative to the Glamaig Granite is available, although it is evident that both granites were intruded before the Marscoite Suite (see below).

The Maol na Gainmhich Granite is a coarse-grained, amphibole-bearing rock that contains only one feldspar, a potassium-rich variety (Figure 9-137). The amphibole is rich in alkalis and has been identified as arfvedsonite. This intrusion crops out north of Loch Ainort, in the ground south of Maol na Gainmhich, between Ceann a' Chreagain and the coast (Figure 9-131). The granite that crops out on the SW coast of the neighbouring island of Scalpay may be from the same intrusion (Wager *et al.*1965).



Figure 9-137: Field image of coarse-grained, amphibole-bearing Maol na Gainmhich Granite. Coin *ca.* 24 mm across.

The Eas Mòr Granite crops out on the NW slopes of Glamaig, being accessible in the stream bed of the Eas Mòr, itself (Figure 9-138). It is characterised by phenocrysts of alkali feldspar, together with relatively abundant green hornblende, set in a fine-grained, quartz and alkali feldspar dominated, groundmass.

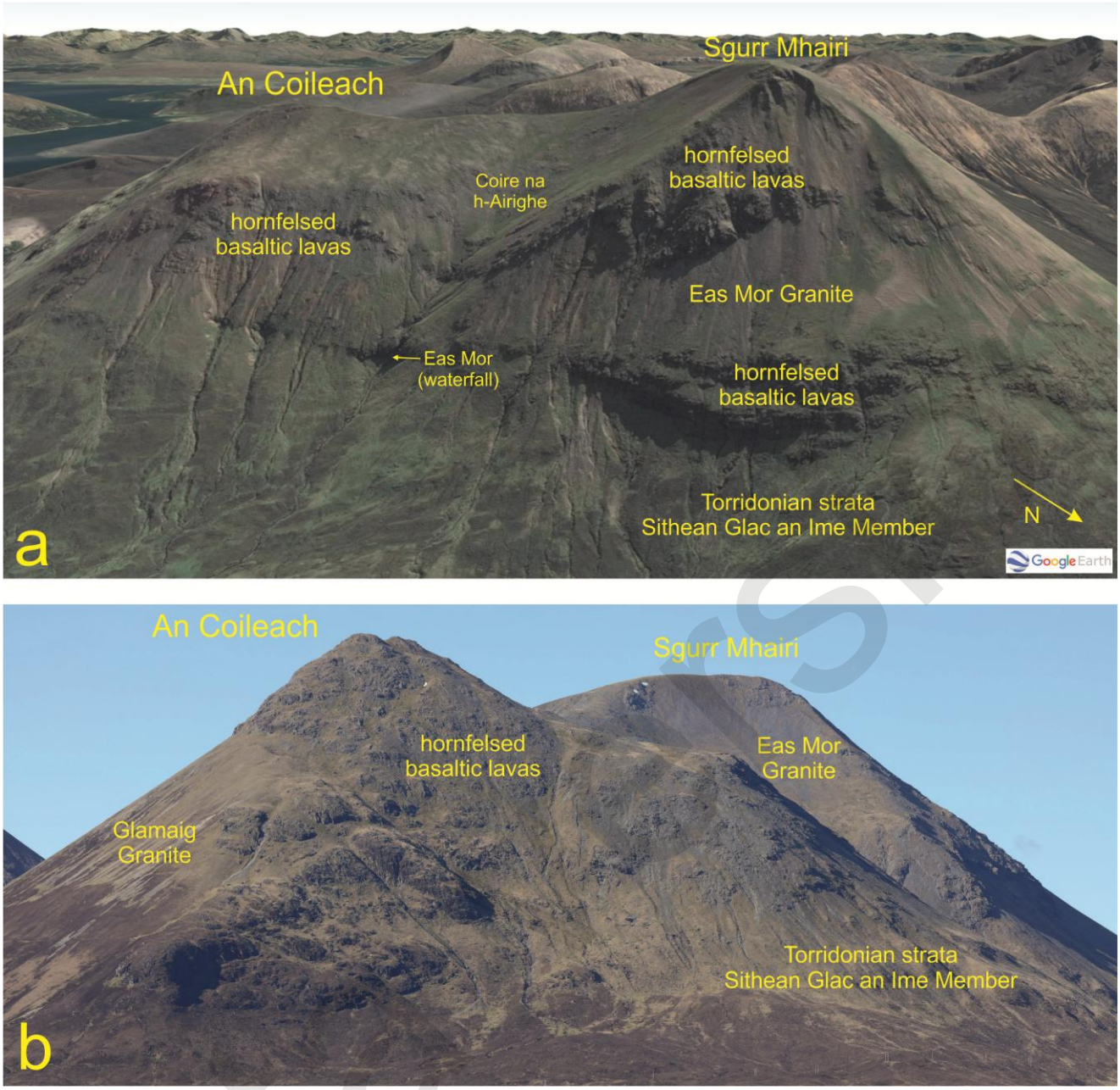


Figure 9-138: (a) Oblique Google Earth© image of the north face of Glamaig, with the relatively easily weathered Eas Mòr Granite, comprising a horizontal outcrop, with hornfelsed country-rock basaltic lavas above and below, view towards the SW; and, (b) annotated field view of An-Coileach – Sgùrr Mhairi (Glamaig), view from Raasay.

9.8.3.5 The Beinn Dearg Mhòr and Loch Ainort Granites (W5 & W6)

The Beinn Dearg Mhòr Granite crops out on the Red Hill of that name (Figure 9-139), as well as on Ciche na Beinne Deirge and Beinn Dearg Mheadhonach, and was originally called the G2 granite by Richey *et al.* (1946). Its inner and outer margins are close to vertical and locally show signs of crushing. Along its boundary with the Glamaig Granite, for example at Am Fuar-choire, it has a chill facies of porphyritic felsite/rhyolite, which clearly indicates the time-relationships between the two intrusions. At Màm a' Phobuill, the Beinn Dearg Mhòr Granite is fractured and altered by the later Southern Porphyritic Granite (see below). Along its inner margin, for example in the Allt Mhic Mhoirein, the Beinn Dearg Mhòr Granite is fractured by the later Loch Ainort Granite (see below).

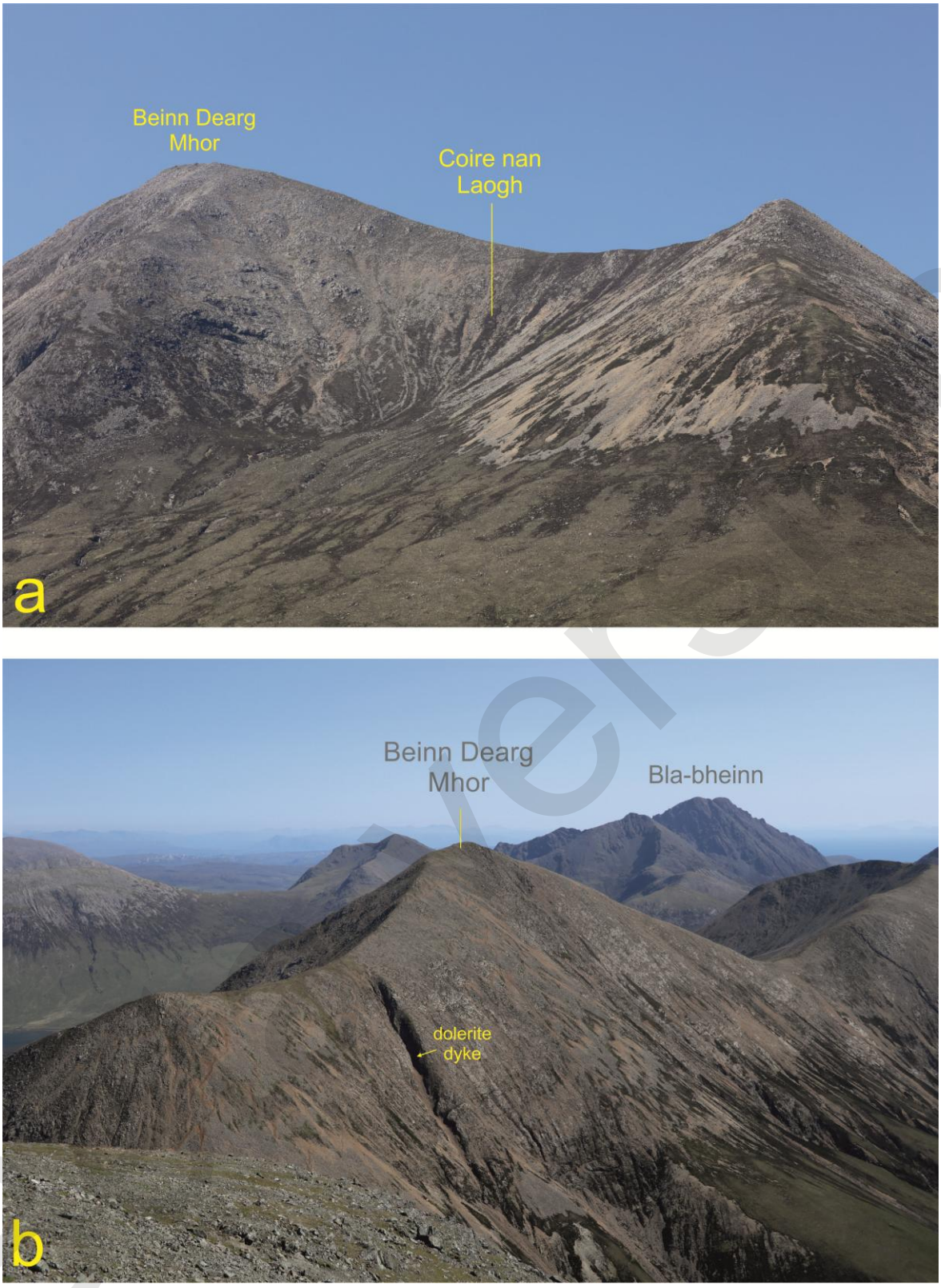


Figure 9-139: (a) The east side of Beinn Dearg Mhòr, composed of the Beinn Dearg Mhòr Granite, view towards the SW from Gleann Torra-mhichaig; and (b) Beinn Dearg Mhòr viewed towards the south from Sgùrr Mhairi (Glamaig).

The Beinn Dearg Mhòr Granite weathers deeply, to a distinct rusty red, in sharp contrast to the grey coloration of the neighbouring, older Glamaig Granite (Figure 9-134). Fresh material is greenish blue. It contains abundant phenocrysts of fresh, glassy anorthoclase, commonly in a glomero-porphyritic arrangement. The groundmass is composed of granophyric intergrowths of quartz and alkali feldspar. The

most common ferromagnesian mineral is the Fe-rich clinopyroxene, ferrohedenbergite, together with some hornblende, Fe-Ti oxides, apatite and biotite. Olivine is not common but, where present, is typically serpentinised.

Around the northern margin of the Beinn Dearg Mhòr Granite, south of the Allt Mòr Doire Mhic-ùin, is a zone of disruption, with large slabs of crushed, altered gabbro forming part of a screen between it and the Glamaig Granite. These slabs were most likely entrained along the contact during the emplacement of the younger Beinn Dearg Mhòr Granite.

The Loch Ainort Granite crops out on the low ground around the head of Loch Ainort, between Maol Bàn in the north, and Coire Choinnich in the south, and is roughly L-shaped, with an area of *ca.* 7 km^2 (Figure 9-136; Figure 9-140; Figure 9-141**)**. Crushing complicates its contacts with the Beinn Dearg Mhòr Granite to the west, the Northern Porphyritic Felsite to the north, and the Southern Porphyritic Granite to the south. It is truncated to the east by the oldest of the granites of the Eastern Red Hills Intrusive Centre, the Glas-Bheinn Mhòr Granite. Its mineralogy is almost identical to the Beinn Dearg Mhòr Granite (see above). The zone of crushing in the northern part of the granite, between Druim nan Cleochd and Leathad Chrithinn, lead J.D. Bell (Bell 1959, 1966) to conclude that the two intrusions are part of the same mass, with upward movement of the inner Loch Ainort Granite, relative to the outer Beinn Dearg Mhòr Granite, bringing about the observed field relationships.

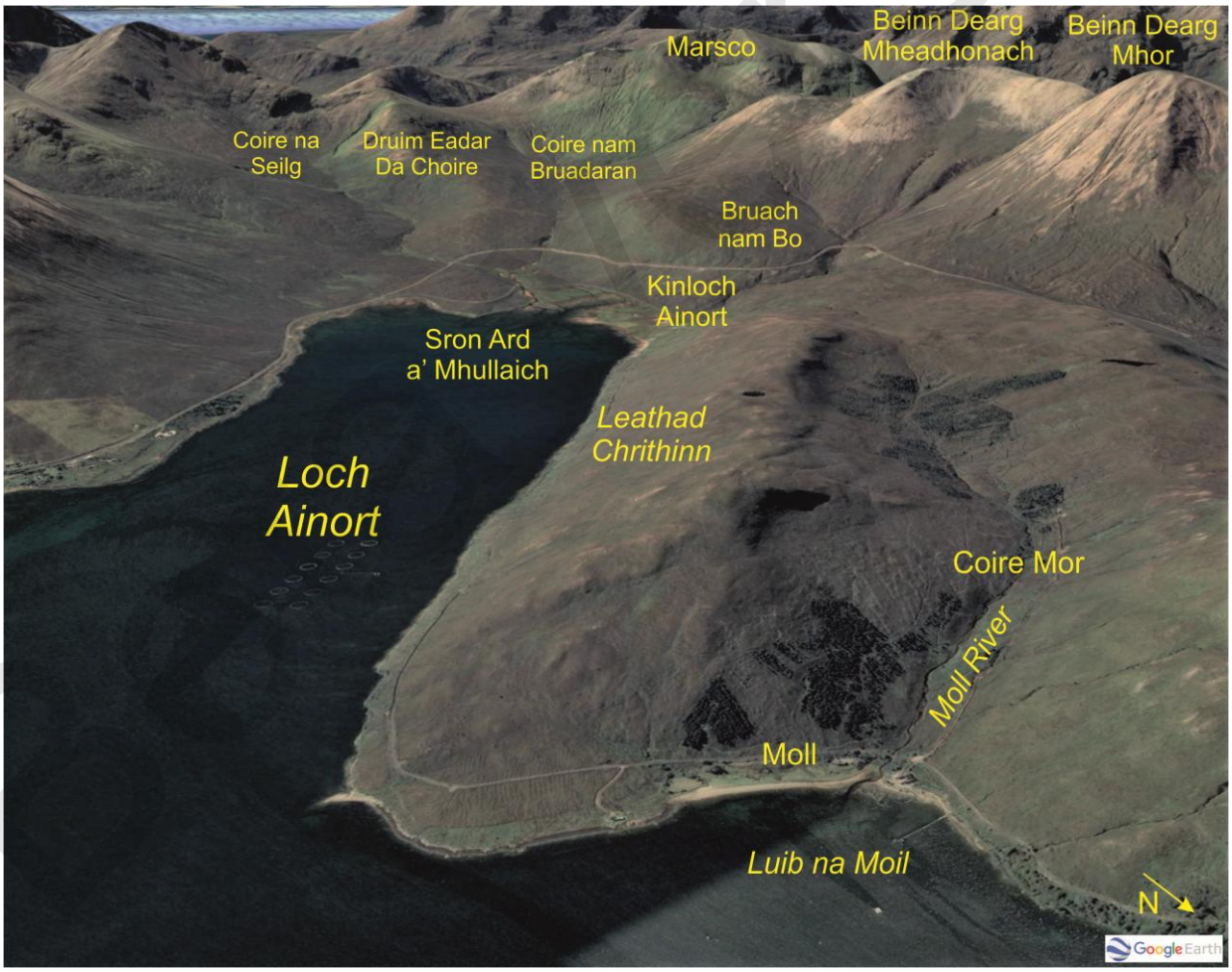


Figure 9-140: Oblique Google Earth© image of the Loch Ainort area, with the Loch Ainort Granite cropping out on the NE side of the loch at Leathad Chrithinn. View towards the SW.



Figure 9-141: Exposure of the Loch Ainort Granite forming the Eas a' Bhradain on the Allt Coire nam Bruadaran at the head of Loch Ainort.

Near the Allt Coire na Cìche, J.D. Bell (Bell 1966) identifies a fine-grained silicic rock containing biotite and amphibole. It is light grey and may either constitute a separate sheet of material intruded between the Beinn Dearg Mhòr and Loch Ainort granites, or a marginal facies of one of them. A small intrusion of similar material is exposed SW of Sròn Ard a' Mhullaich, at the head of Loch Ainort. Essentially, these are porphyritic felsites/rhyolites, containing feldspar phenocrysts of the same type present in the granites. Locally, the felsites have gradational contacts with the granites.

9.8.3.6 The Glen Sligachan and Southern Porphyritic Granites (W2 & W3)

The Glen Sligachan Granite (Figure 9-142) has a very limited outcrop, *ca.* 750 m x 100 m, along the northern side of the Marscoite Suite (see below), at the base of Harker's Gully on Marsco (Figure 9-136). It weathers to a rusty brown, although when fresh is bluish grey, with a distinctly porphyritic character. The phenocrysts of feldspar consist of plagioclase cores, rimmed with alkali feldspar, together with crystals of microperthite. Ferrohedenbergite and olivine (generally altered) are present in small quantities.

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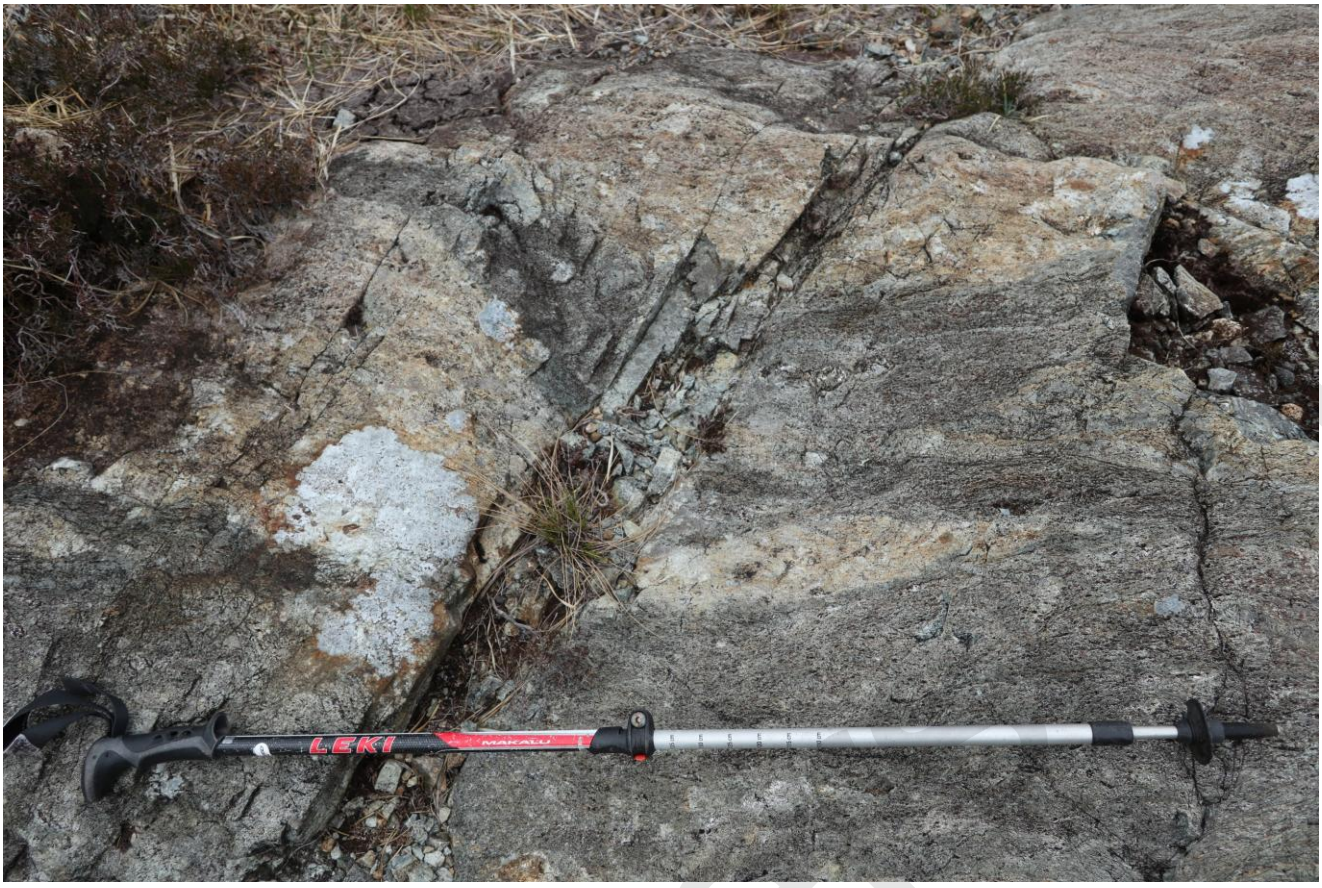


Figure 9-142: Sheared Glen Sligachan Granite, east of the Sligachan – Camasunary path. Pole *ca.* 1 m long.

The Southern Porphyritic Granite (Figure 9-136; Figure 9-143) is exposed in a broad tract of ground north of the Marscoite Suite (see below), between Màm a' Phobuill in the west and the Allt a' Mheadhoin in the east, and to the south of the Marscoite Suite, at Fiaclan Dearg, on Marsco (Figure 9-136). Along the northern margin of the main outcrop, dipping at 60° to the south, the Southern Porphyritic Granite cuts the Glamaig, Beinn Dearg Mhòr and Loch Ainort granites, although well-defined contacts are not exposed. The southern margin of this outcrop of the granite is almost vertical and there is an extensive development of a marginal chill facies of felsite/rhyolite (see below). The outcrop of the Southern Porphyritic Granite south of the Marscoite Suite has the form of a ring-dyke roof fragment, lying below the older Glamaig Granite, and above the younger Marsco Granite (see below).

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Figure 9-143: Contact between the Southern Porphyritic Granite (with wide-spaced joints; left side of exposure) and the Southern Porphyritic Felsite (with narrow-spaced joints; right side of exposure). NW side of Marsco, north of Harker's Gully (*ca.* 100 m above the Shelter Stone). Pole *ca.* 1 m long, located at contact.

This pale-weathering granite contains phenocrysts of quartz and clouded alkali feldspar, set in a granophyric groundmass. Thompson (1969) recorded the presence of small amounts of ferrohedenbergite, olivine, amphibole and biotite. Crushing is a common feature within the Southern Porphyritic Granite, and this led Wager *et al.* (1965) to suggest that a high H_2O pressure developed during its crystallisation.

The marginal felsite/rhyolite facies, along the contact with the Marscoite Suite (see below), is referred to as the Southern Porphyritic Felsite and contains the same phenocryst assemblage as the closely related granite, but is set in a felsitic, or fine-grained to glassy, groundmass. Wager *et al.* (1965) concluded that the felsite constitutes a thin, separate sheet of material injected into the granite after it had been crushed, but whilst still hot. The felsite was most likely derived from the same magma source as the Southern Porphyritic Granite but clearly cooled much faster and was most likely depleted in volatiles. The significance of the Southern Porphyritic Felsite, in relation to magma mingling/mixing processes in the Western Red Hills Intrusive Centre, is discussed below.

9.8.3.7 The Marscoite Suite (M)

The Marscoite Suite forms a partially preserved composite ring-dyke within the WRHIC and was first identified as a distinct group of rocks by Wager *et al.* (1965), and includes: porphyritic felsite/rhyolite, ferrodiorite, and the (locally named and used) hybrid rocks marscoite, glamaigite and dioritic glamaigite. The ring-dyke's main and most important outcrop forms a prominent gully on the NW side of Marsco (Figure 9-136; Figure 9-144; Figure 9-145). The hybrid nature of marscoite was first deduced by Alfred

Harker (Harker 1904) and, to honour his remarkable insight, the gully formed by the inweathering of the ring-dyke was informally named ‘Harker’s Gully’ by Wager *et al.* (1965).

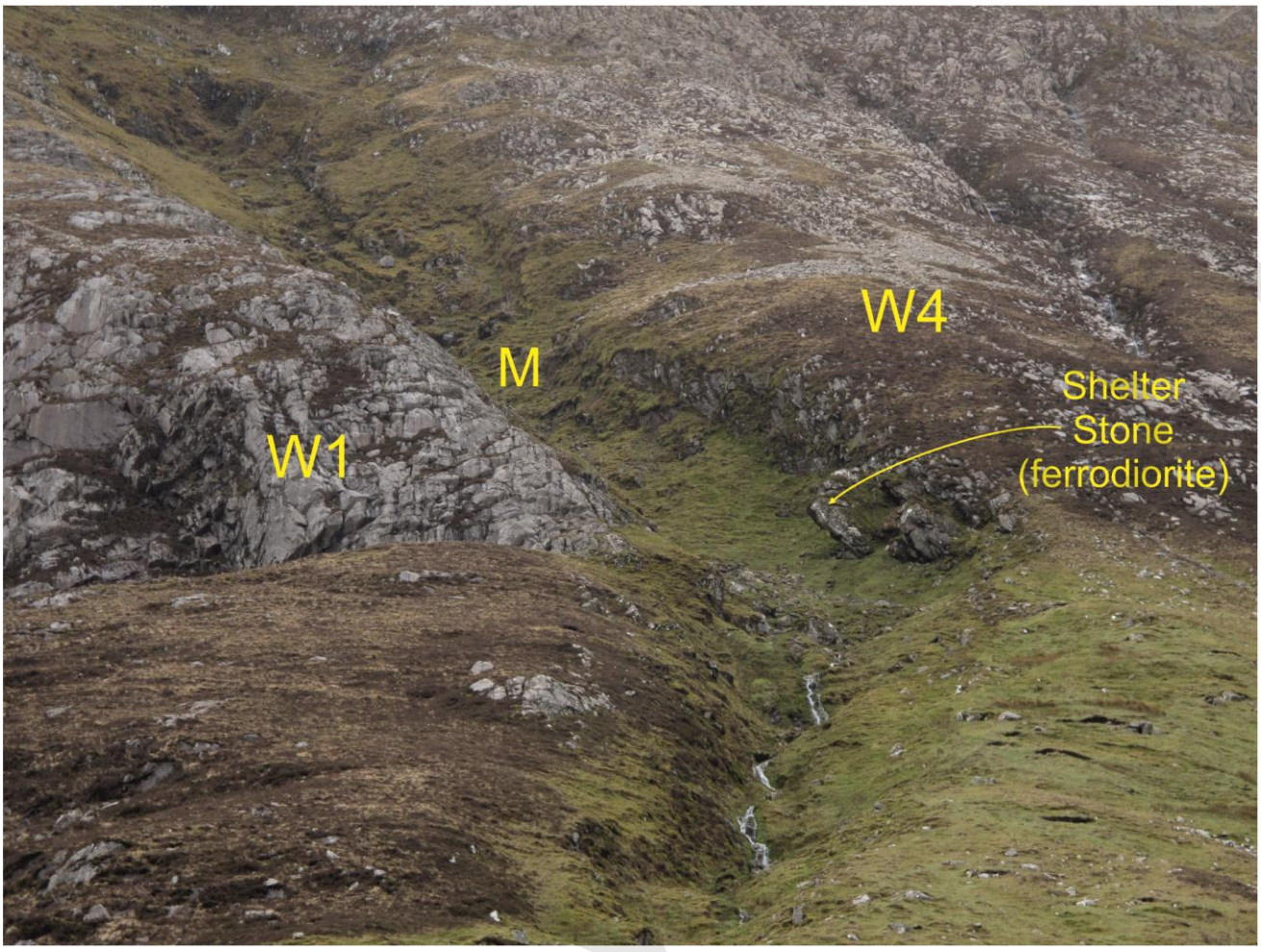


Figure 9-144: The lower part of Harker’s Gully on the NW side of Marsco, marking the location of the Marscoite Suite (M) of rocks forming part of a composite ring-dyke within the WRHIC. W1: Glamaig Granite; W4: Marsco Granite. The protruding rock on the south (right) side of the gully is the Shelter Stone, composed of ferrodiorite.

From exposures in Harker's Gully, on the NW side of Marsco, Wager *et al.* (1965) were able to deduce the field relationships of the porphyritic felsite/rhyolite, the ferrodiorite and the marscoite units/lithologies (Figure 9-136), and suggested that marscoite was formed by mechanical mingling/mixing of porphyritic felsite/rhyolite and ferrodiorite magmas. Based on simple calculations, Wager *et al.* (1965) concluded that the mixing of *ca.* 65% of ferrodiorite magma (an Fe-enriched fractionate of tholeiitic basalt magma) and *ca.* 35% of porphyritic felsite/rhyolite magma (the Southern Porphyritic Felsite, see below) would result in a magma with the composition of marscoite. Confirmatory mineralogical evidence for the hybrid nature of marscoite is readily obtained from thin-section studies. For example, this fine-grained, grey rock contains xenocrysts of andesine (with rounded edges), orthoclase (with embayed margins, the so-called fingerprint texture) and quartz (fringed with either pyroxene or amphibole), all of which can be identified as phenocrysts in the postulated basic and silicic parents (the andesine in the ferrodiorite and the orthoclase and quartz in the porphyritic felsite).

The ferrodiorite tends to be the most easily weathered of the three lithologies and is responsible for the gully’s development. Locally, it has well developed spheroidal/doleritic/onion skin weathering, typical of mafic rocks (Figure 9-145) and occurs in two varieties: with or without distinct phenocrysts of andesine

(zoned from An_{50} to An_{30}). The groundmass is composed of turbid crystals of alkali feldspar, interstitial quartz, inverted pigeonite, augite and olivine (Fo_{22}, typically altered to serpentine), together with accessory apatite, zircon, Fe-Ti oxides and pyrrhotite. Also present within the ferrodiorite intrusion are large (10–30 cm) inclusions of andesinite, an essentially monomineralic lithology of plagioclase (andesine) crystals. These inclusions are also found within the marscoite but are much less common. Xenoliths of Lewisian Gneiss (Chapter 2) occur within the ferrodiorite intrusion in Harker's Gully and in the Allt Coire nam Bruadaran (Figure 9-146).



Figure 9-145: Typical spheroidal weathering of ferrodiorite on the north side of Harker's Gully at the Shelter Stone level. Pole *ca*. 1 m long.

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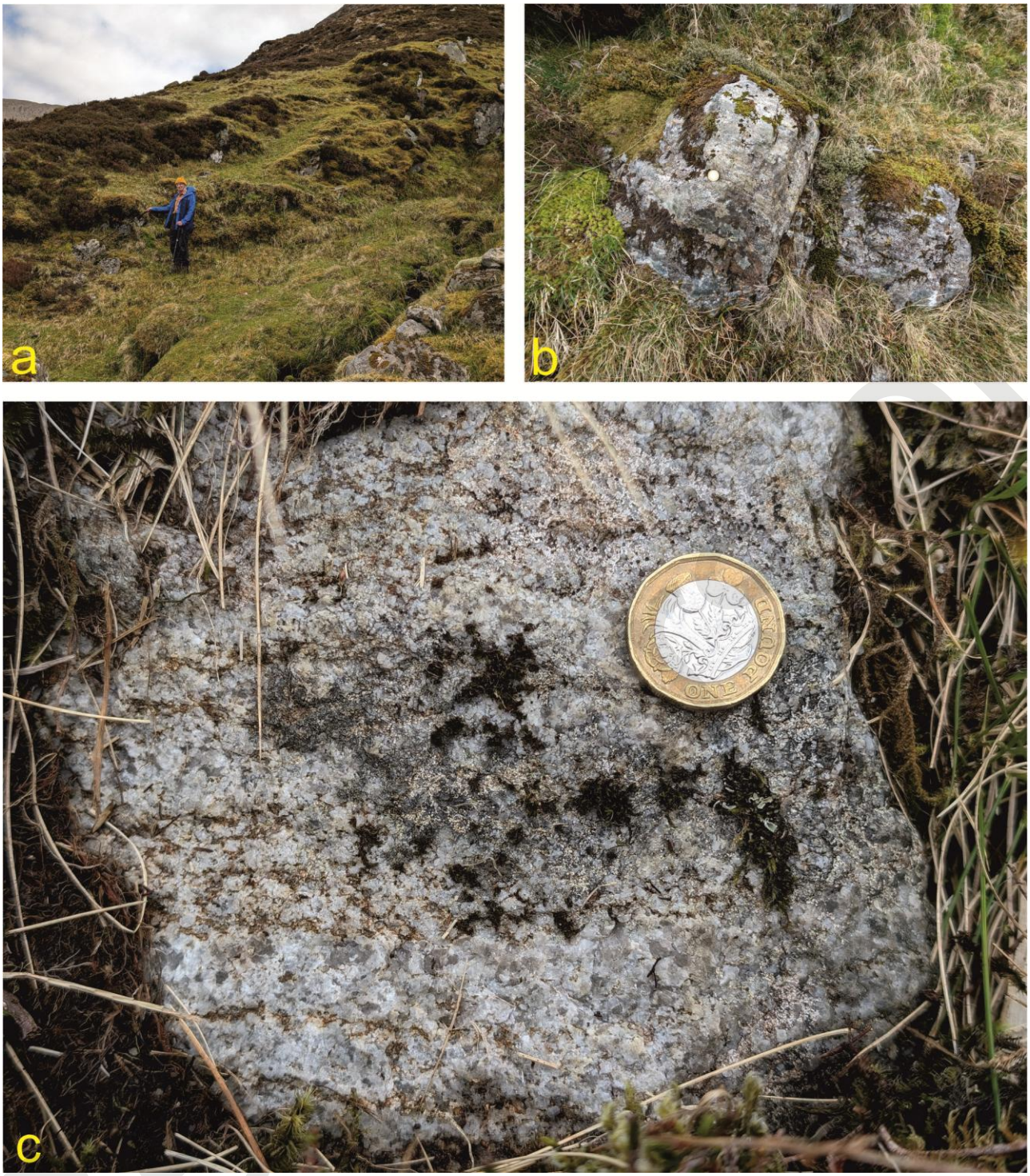


Figure 9-146: Xenolith of banded gneiss within the ferrodiorite intrusion of the Marscoite Suite close to the base of Harker's Gully on the NW side of Marsco. Coin *ca*. 24 mm.

On the north side of Harker's Gully, the Southern Porphyritic Felsite, marscoite and ferrodiorite occur as relatively thin, steeply inclined sheets, which constitute part of a large, outward-dipping, composite ring-dyke that can be traced, albeit discontinuously, from Marsco in the west, to Coire Choinnich in the east (Figure 9-147; Figure 9-148).

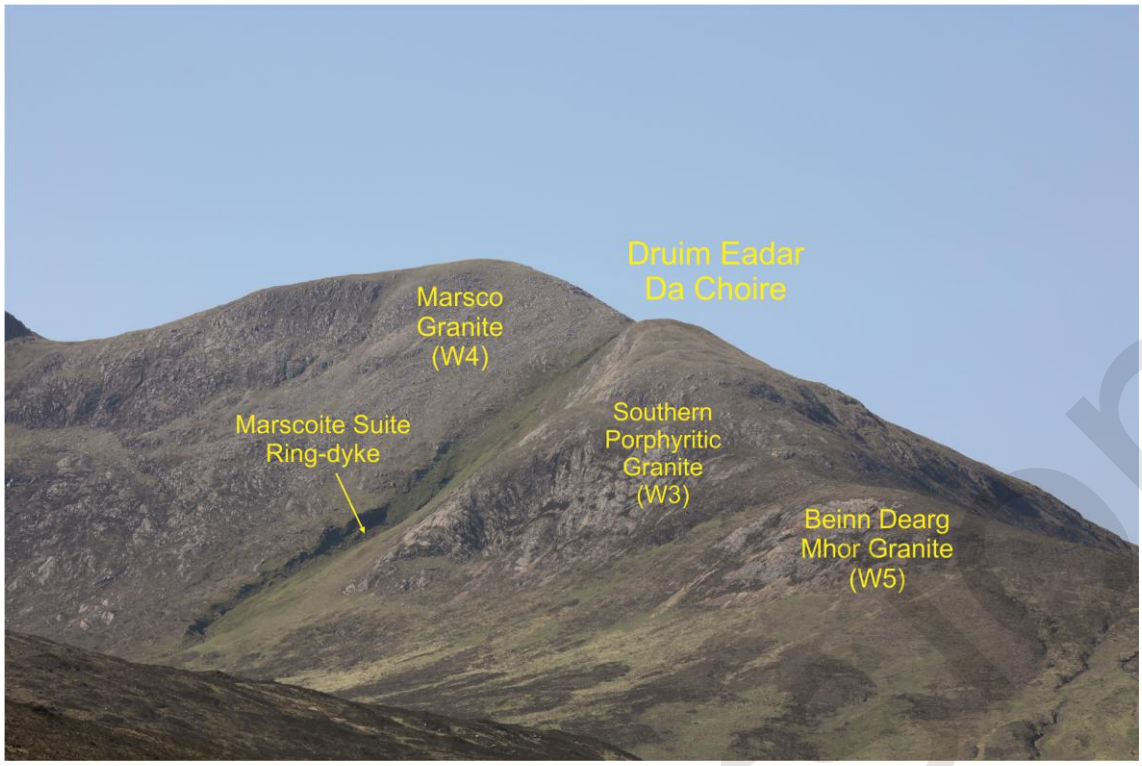


Figure 9-147: Trace of the Marscoite Suite ring-dyke, forming a trench-like feature on the east side of Druim Eadar Dà Choire, flanked by the Southern Porphyritic Granite and the Marsco Granite. View towards the SW.



Figure 9-148: Detail of Marscoite Suite ring-dyke, Druim Eadar Dà Choire

On Marsco, at the level of the Shelter Stone, the following field relationships can be deduced (Wager *et al.* 1965) (Figure 9-149). First, marscoite chills against, and rarely veins, the Southern Porphyritic Felsite, although their bulbous mutual boundary suggests that the latter had not totally crystallised. Second, the

marscoite grades over *ca*. 10 m into porphyritic ferrodiorite, suggesting that the two intrusions were emplaced almost synchronously, and that *in situ* mingling/mixing (both mechanical and diffusional) has destroyed any sharp boundary that may have existed between the two.

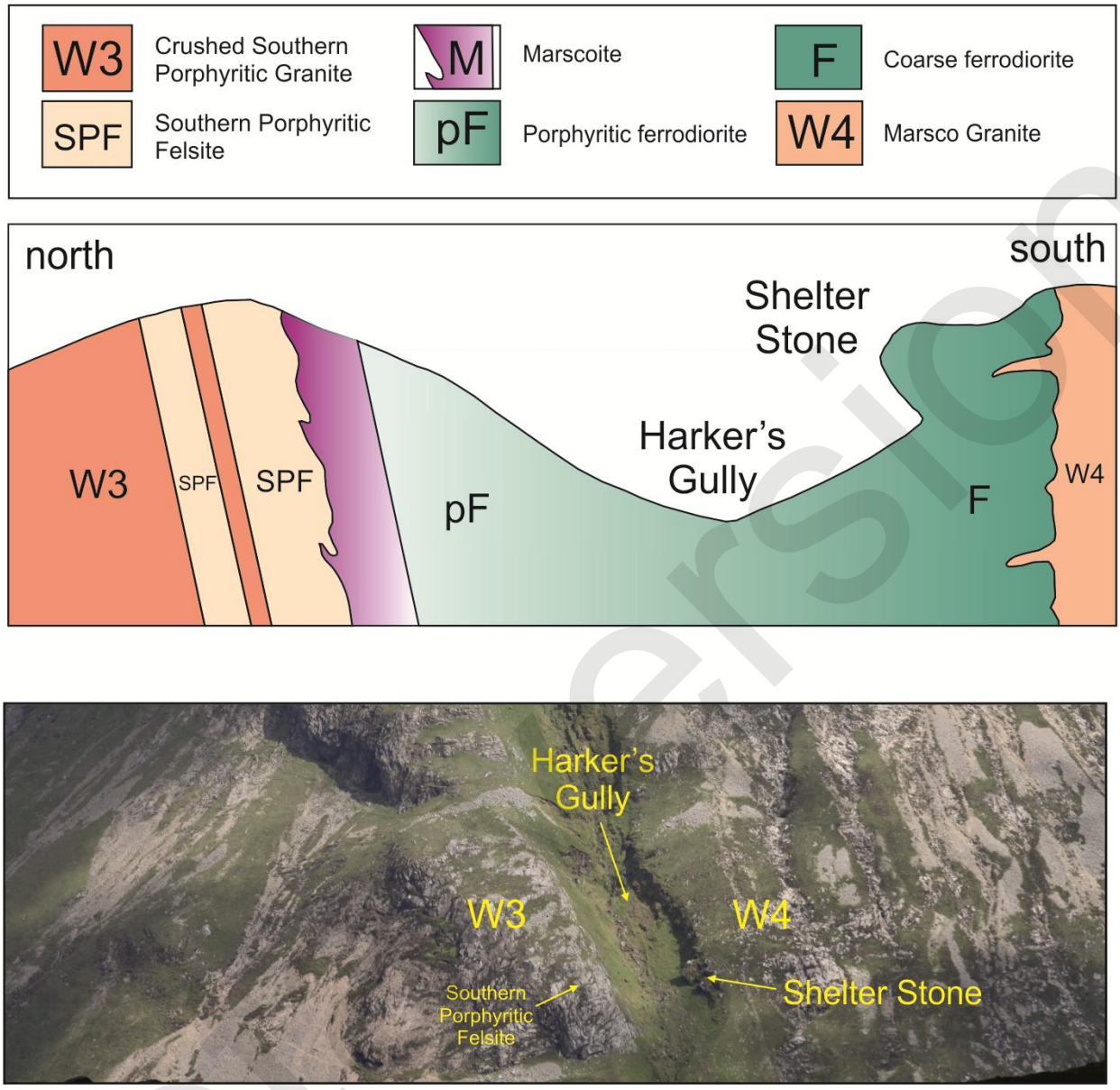


Figure 9-149: Schematic cross-section through the Marscoite Suite at the level of the Shelter Stone in Harker's Gully on the NW side of Marsco (after Wager *et al*. 1965).

On the south side of the gully, the ferrodiorite is coarser-grained and non-porphyritic. Typical ferrodiorite forms the overhanging Shelter Stone (Figure 9-149). On this side of the gully, the ferrodiorite is in contact with the Marsco Granite, one of the youngest of the Western Red Hills major granitic intrusions (see below).

A subsequent investigation of these rocks by Thompson (1969) reports quartz xenocrysts within the ferrodiorite, suggesting that it, too, is a hybrid rock. At the top of Harker's Gully, above the roof of the Marsco Granite, Thompson (1969) identified a complete (and symmetrical) section through the ring-dyke (Figure 9-150). The section consists of felsite-marscoite-ferrodiorite-marscoite-felsite and confirms the previously deduced sequence of intrusive events as: felsite, followed by marscoite, followed by ferrodiorite.

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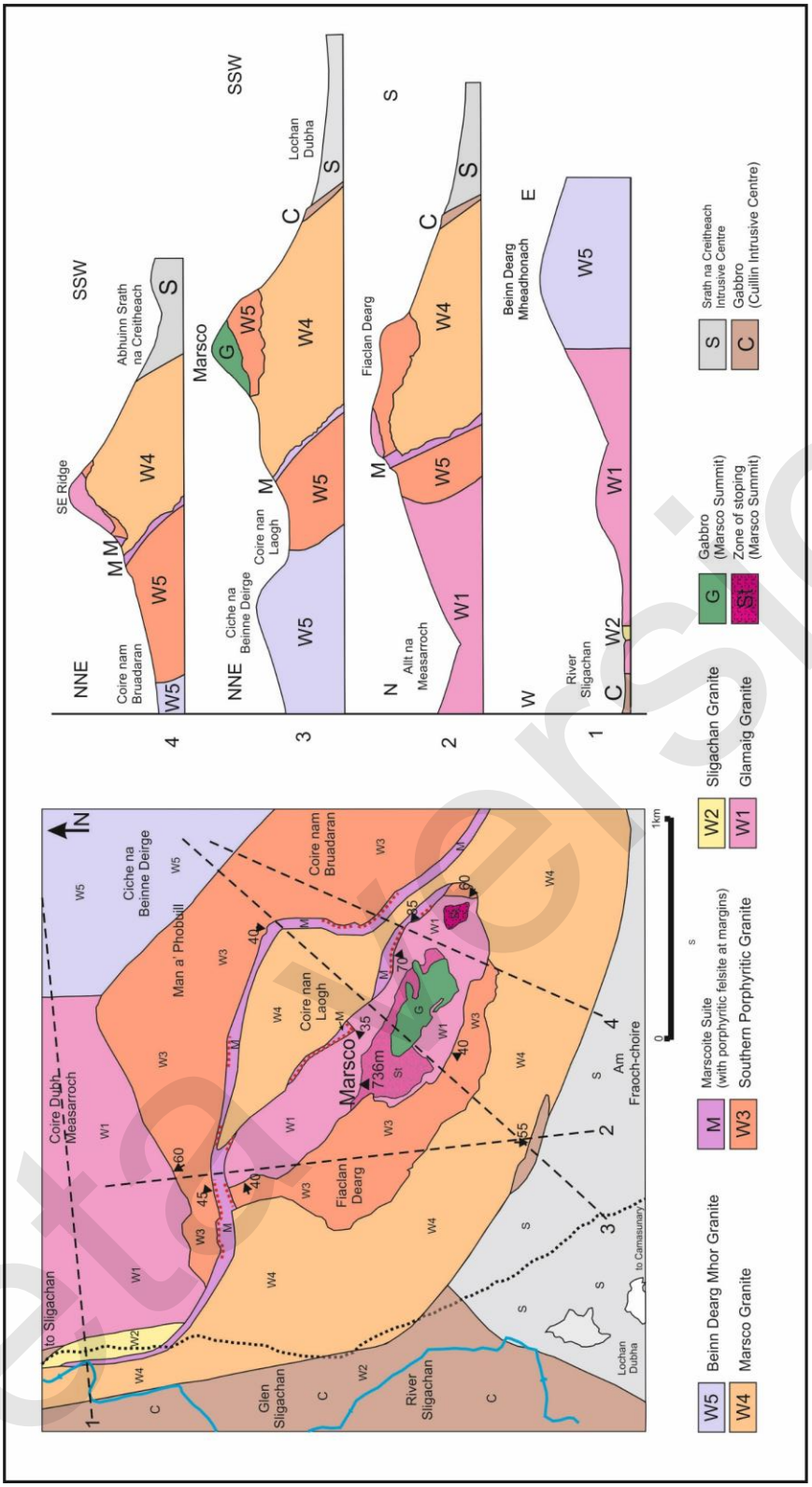


Figure 9-150: Schematic cross-sections through the Marsco area (after Thompson 1969).

Members of the Marscoite Suite in the northern part of the WRHIC crop out as three separate intrusions, referred to by Wager *et al.* (1965) as the Glamaig, Meall Buidhe and Moll Shore intrusions (Figure 9-151). In addition to marscoite, two other (locally named and used) hybrid rocks are identified within these composite intrusions: glamaigite and dioritic glamaigite.

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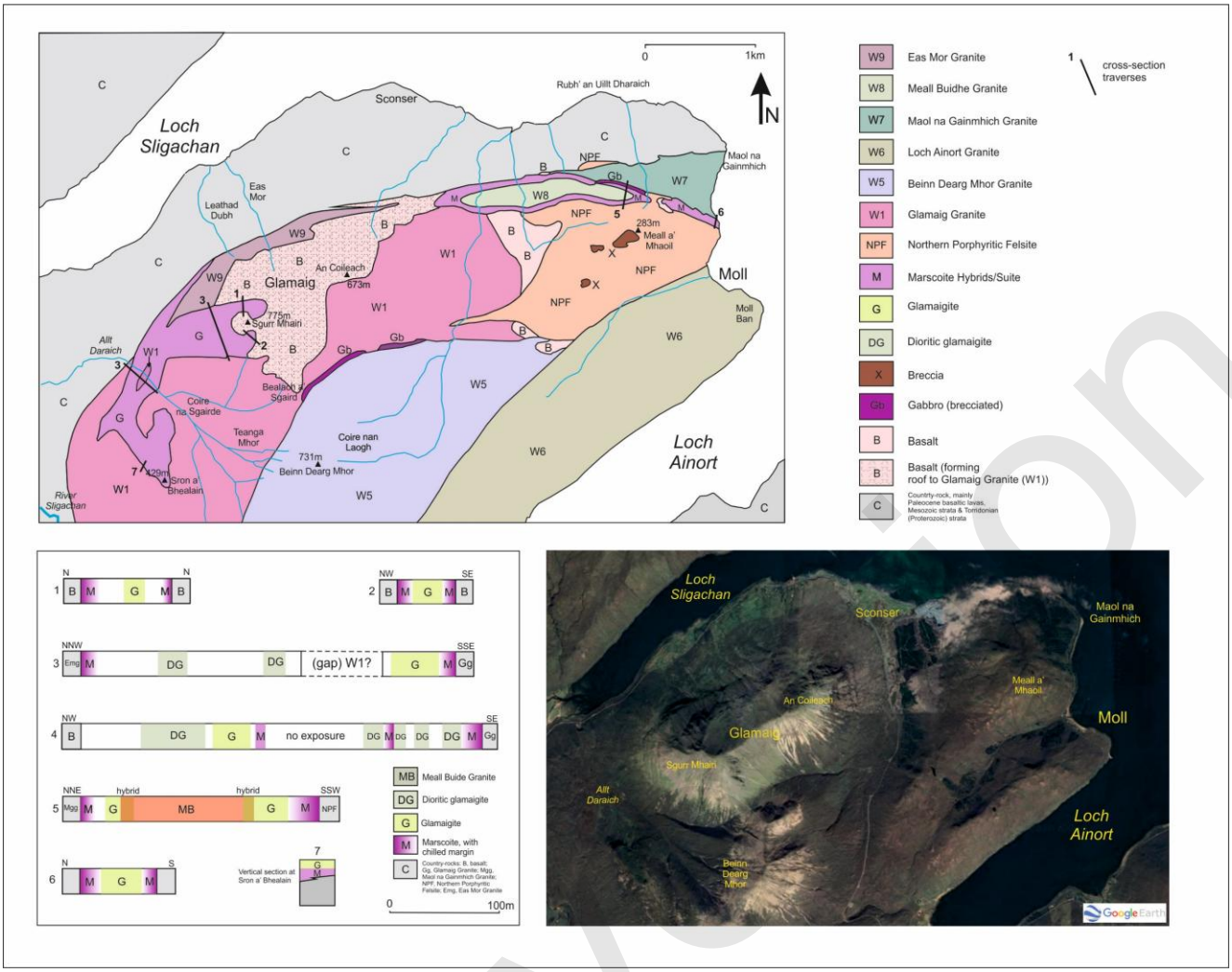


Figure 9-151: Schematic cross-sections through Marscoite Suite in the northern part of the WRHIC (after Wager *et al.* 1965), and Google Earth© image of the same area.

The Glamaig Hybrid Intrusion consists of an inclined sheet cutting the granites and lavas SW of the summit of Glamaig and on Sròn a' Bhealain. The attitude of this sheet is most readily determined in the Allt Daraich, where it dips at *ca.* 45° to the NW. On Sròn a' Bhealain, the dip is much less, *ca.* 5°, in the same general direction. The Meall Buidhe Hybrid Intrusion is exposed in the ground between the hill of that name and the Abhainn Torra-mhichaig, further west, and forms an almost-vertical sheet. The Moll Shore Hybrid Intrusion is, in many ways, similar, and is exposed along the road-cuts south of Maol na Gainmhich. The disposition of these intrusions suggests that they have the same steep-sided, incomplete ring-dyke form as the Marscoite Suite exposed in the southern portion of the WRHIC (see above).

The margins of all three northern hybrid intrusions consist of chilled marscoite, which grades over *ca.* 1 m into 'normal' marscoite. 10–20 m beyond, the rock takes on a heterogeneous, streaky (or net-veined) appearance, passing into, over the next 10 m, a hybrid rock referred to by Wager *et al.* (1965) as glamaigite (Figure 9-152). This is the rock which Harker (1904) described as a xenolithic granophyre, believing it to have formed by the mixing of marscoite and a granitic magma (see below). Towards the centres of the three hybrid intrusions, a more homogeneous facies of glamaigite is preserved, which Wager *et al.* (1965) referred to as dioritic glamaigite. Sections through the three hybrid intrusions are of the symmetrical form: marscoite-glamaigite-dioritic glamaigite-glamaigite-marscoite.

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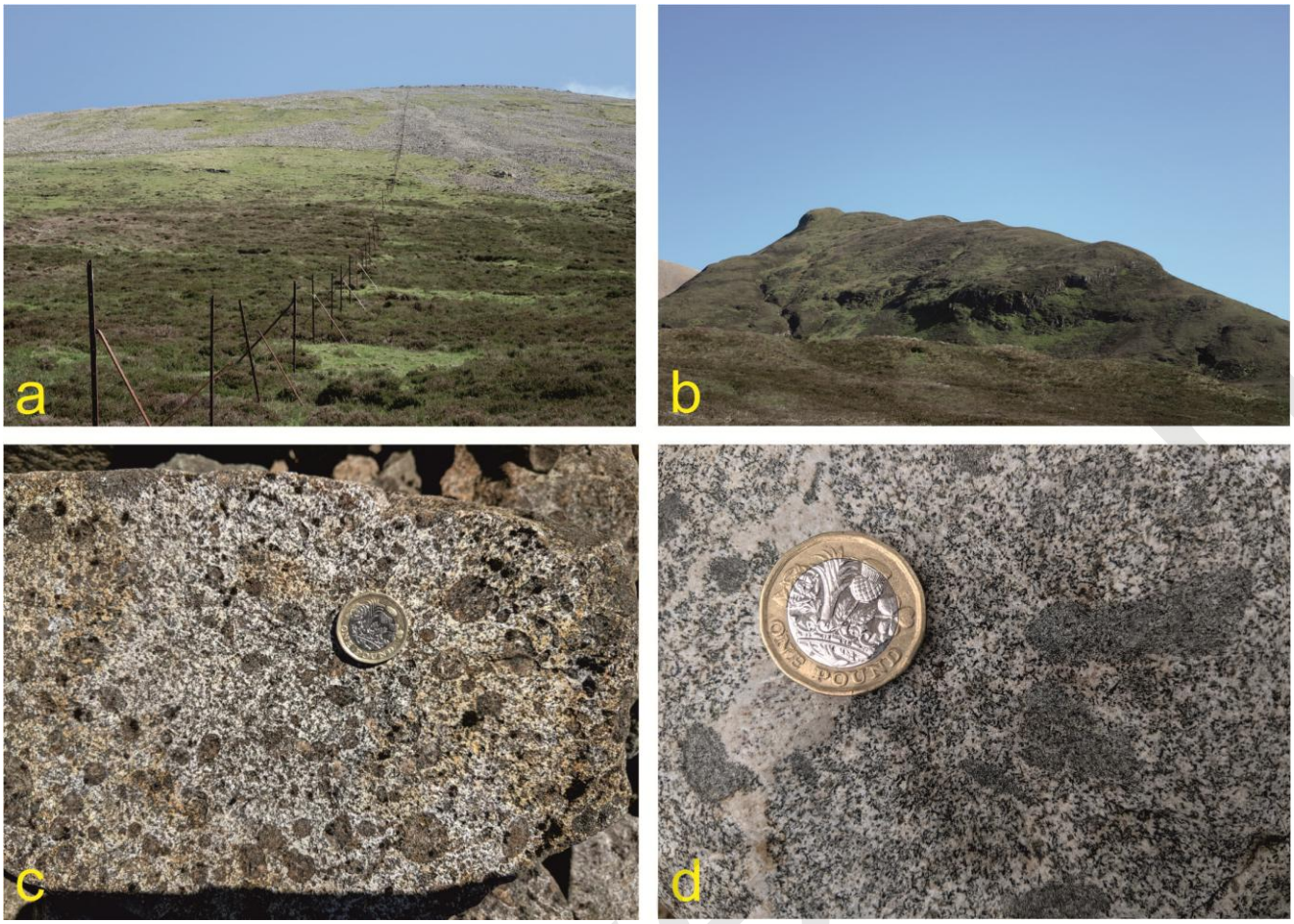


Figure 9-152: (a) SW side of Glamaig, dominated by a scree of glamaigite; (b) north face of Sròn a' Bhealain, composed of an inclined sheet of glamaigite, view towards the SW from Glamaig; and, (c) & (d) hand specimens of glamaigite, comprising contrasting dark (mafic) and pale (silicic) components in an arrested state of mixing (hybridisation). Coin *ca*. 24 mm across.

In the centre of the glamaigite unit of the Meall Buidhe Hybrid Intrusion is a silicic intrusion, the Meall Buidhe Granite (see below).

Xenoliths and xenocrysts are common within the northern marscoite-glamaigite intrusions. Andesinite is the commonest xenolith type, together with glomero-porphyritic patches of xenocrystic plagioclase. Also present are smaller, rounded masses of fine-grained basic material containing plagioclase phenocrysts with compositions of An_{50} and whole-rock compositions approximating to that of hawaiite.

From simple calculations, Wager *et al*. (1965) suggested that the northern marscoites of the Glamaig, Meall Buidhe and Moll Shore hybrid intrusions were generated by the mixing of *ca*. 40% porphyritic felsite magma (Southern Porphyritic Felsite) with *ca*. 60% basic (hawaiitic) magma.

The heterogeneous nature of the glamaigite intrusions suggests that they, too, have formed by various mingling/mixing processes. For example, detailed microscopic studies show that the dark patches characteristic of glamaigite, most readily identified on weathered surfaces, and the paler 'matrix' material have mineralogies like that of typical marscoite. Thus, glamaigite has at least two distinct parts, both essentially marscoites, and both containing xenocrysts of andesine, quartz and alkali feldspar. It is clear, therefore, that the heterogeneous and homogeneous forms of glamaigite have had long, complex histories.

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9.8.3.8 The Northern Porphyritic Felsite and the Meall Buidhe Granite (NPF & W8)

The Northern Porphyritic Felsite (NPF) crops out over an area of *ca.* 2 km^2 south of Meall Buidhe and has many features in common with the Southern Porphyritic Felsite (see above) (Figure 9-153). However, no equivalent granite can be correlated, at the present level of erosion, with this felsite. Like the Southern Porphyritic Felsite, the NPF contains phenocrysts of quartz and alkali feldspar (and in the same relative proportions) but differs in terms of its greater absolute amount of these phenocrysts. A further distinctive feature is the presence of small (2–10 cm) fragments of basic material dispersed throughout the intrusion. This material is similar, but not identical, to the inclusions within the Glamaig Granite (see above). The NPF has a thin crush zone where it is in contact with older country-rock basaltic lavas and the Glamaig Granite.



Figure 9-153: Typical weathered surface of the Northern Porphyritic Felsite, with (rusty) alkali feldspar and grey quartz phenocrysts. Coin *ca.* 24 mm across.

The Meall Buidhe Granite occurs within the northern marscoite-glamaigite Meall Buidhe Hybrid Intrusion (Figure 9-151), which crops out in the area between Meall Buidhe and the Abhainn Torra-mhichaig. The best exposures are in the Allt a' Bhealaich Bhric, where its close relationship with these hybrid rocks is readily noted. The Meall Buidhe Granite is a microgranite, containing phenocrysts of oligoclase rimmed with altered alkali feldspar, set in a groundmass dominated by quartz and alkali feldspar. Also present are small quantities of pyroxene, a green amphibole, a green biotite, and a small amount of serpentinised olivine. These mineralogical features led Wager *et al.* (1965) to conclude that this intrusion is like the Marsco Granite (see below), the youngest of the granites of the WRHIC (see below).

9.8.3.9 The Marsco Granite (W4)

The Marsco Granite crops out on the southern and western sides of Marsco (Wager *et al.* 1965; Thompson 1969) (Figure 9-131; Figure 9-136). It is readily identified by its non-porphyritic character, is pale blue when fresh (pale brown when weathered) and can be accessed at the level of the Shelter Stone (Figure 9-149). The northern margin of this granite against the slightly older ferrodiorite intrusion of the Marscoite Suite/Ring-dyke (see above) dips steeply to the south. These time-relationships are suggested by rare veins of Marsco Granite that penetrate the ferrodiorite, and by the disruption of members of the Marscoite Suite by the Marsco Granite in Coire nan Laogh. However, Thompson (1969) notes that where the Marsco Granite is in contact with ferrodiorite there is evidence that the latter had not completely crystallised. Along such contacts are hybrid rocks, suggesting that some form of mixing/interaction process has taken place, albeit locally. The flat-lying roof of the Marsco Granite crops out at *ca.* 500 m OD, below Fiaclan Dearg (Figure 9-154), although in places apophyses of the intrusion vein and stope the older, overlying Southern Porphyritic Granite at higher levels.

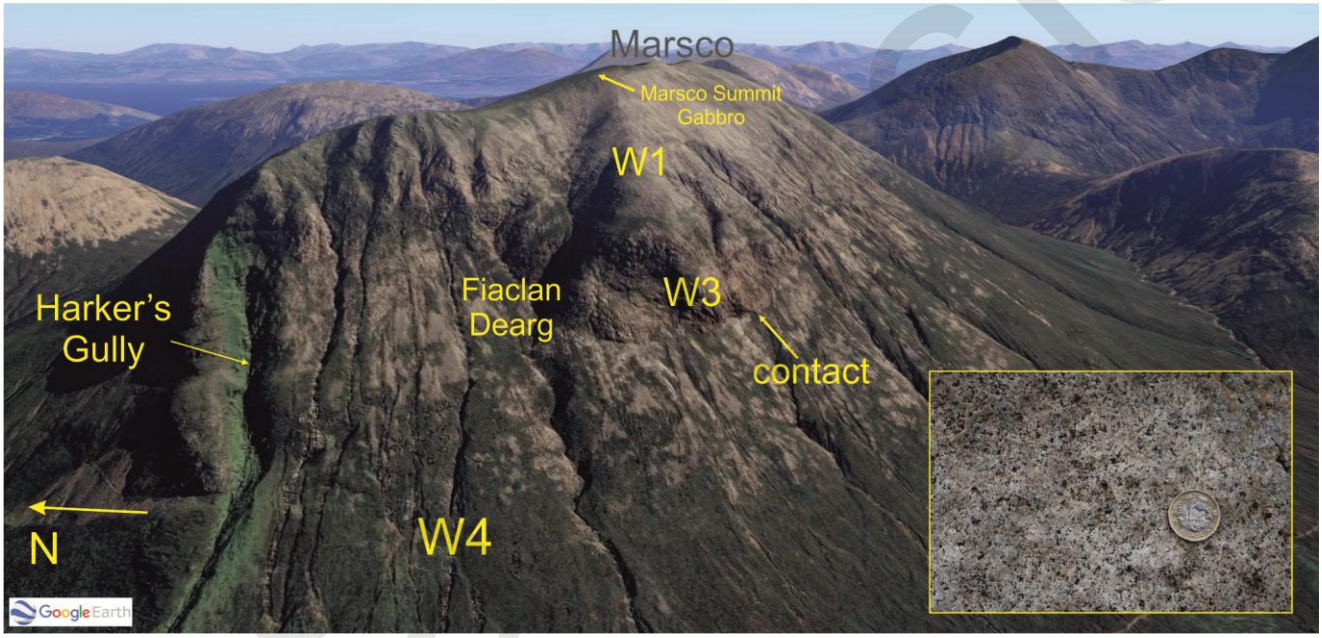


Figure 9-154: Oblique Google Earth© image of the flat-lying contact between the (lower) Marsco Granite (W4) and the (upper) Southern Porphyritic Granite (W3) on Fiaclan Dearg on the west side of Marsco. W1: Glamaig Granite. View towards the east. Inset: field view of typical (non-porphyritic) Marsco Granite, coin *ca.* 24 mm across.

The primary mineralogy of the Marsco Granite consists of quartz, alkali feldspar and plagioclase (An_{24}), together with ferrohedenbergite and fayalite in the lower parts of the intrusion, and amphibole near to the roof zone. Accessory apatite, zircon, allanite and Fe-Ti oxides are also present. A significant feature of the Marsco Granite is miarolitic cavities, especially within the roof zone of the intrusion, which are lined with quartz, alkali feldspar, amphibole and Fe-rich mica (Thompson 1969).

9.8.3.10 Mechanisms of intrusion and volcanic processes

Emplacement mechanisms and possible links with volcanic processes of the intrusions of the WRHIC have been considered in detail by Thompson (1969, 1980), who makes the following observations: (a) two distinct structural groups of granites are present, one elongated N-S (Glamaig, Beinn Dearg Mhòr and

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Loch Ainort granites), the other and later, oriented E-W (Figure 9-131), with members of the N-S group intruded sequentially inwards, whereas the E-W group were emplaced sequentially outwards; (b) all of the intrusions are approximately co-focal about a point east of Loch Ainort; (c) the outcrop patterns of the early granites have the appearance of steep-sided ring-dykes that have been disrupted and partially destroyed by later granites, whereas the later granites have shapes more akin to short arcs of circles, which taper towards their edges; and, (d) permissive emplacement of the intrusions is strongly suggested by the general lack of disturbance of the surrounding country-rocks.

Thompson (1969, 1980) suggested the following cauldron subsidence model for the development of the WRHIC. After the formation of various breccias and the emplacement of the sheet-like Marsco Summit Gabbro (see above), the first of the granites (the Glamaig Granite) was emplaced as a steep-sided mass in the Glamaig area. This was followed, along its concave side, by the Beinn Dearg Mhòr and Loch Ainort granites, which are petrographically and compositionally very similar. At this stage the subsided, central block was jammed against the country-rocks along part of the ring-fracture zone, possibly in the vicinity of Glen Sligachan. Successive tilting of this block about an E-W oriented axis permitted the intrusion of the various members of the Marscoite Suite (see above) and the later granites. With each successive tilt of the block, similar, but not identical, intrusions would be emplaced in the northern and southern sectors of the intrusive centre. Thus, the distinctive differences between members of the Marscoite Suite preserved in the two parts of the WRHIC might be explained.

In their investigation of the Marscoite Suite, Wager *et al*. (1965) concluded that the mixing events associated with the hybrid rocks, marscoite, glamaigite and dioritic glamaigite, occurred within a deeper-level magma chamber. They suggest that two compositionally contrasting magmas, a structurally lower more basic magma (either ferrodioritic or hawaiitic) and an upper more silicic magma (porphyritic rhyolite/felsite), existed as discrete components within the chamber because of their different physical and chemical properties. Convective currents within each of these magmas caused mechanical mingling/mixing to take place along their mutual boundary/interface. The subsequent emplacement of batches of the silicic magma, the basic magma, a homogeneous hybrid (marscoite), or a heterogeneous/inhomogeneous hybrid (glamaigite), in either the southern or northern sectors of the intrusive centre, provides a suitable mechanism for explaining the various complex rock associations described above.

Thompson (1980) and Bell (1983) suggest that these mixing events may have been triggered by the injection of primitive, basic magma into a chamber already containing either silicic magma or silicic magma ponded above a fractionating basic magma. Mixing between these contrasting magmas would produce the hybrids, marscoite and glamaigite.

Another feature of this type of mingling/mixing process would be the entrainment of blebs of the basic magma into the silicic magma. Thompson (1980) suggests that the basic inclusions that typify the Glamaig Granite (see above) originated in this way. The same argument may be applied to the Northern Porphyritic Felsite (see above), which, similarly, contains small inclusions of basic material.

The emplacement of these annular, hybrid intrusions (Glamaig Granite, marscoite and glamaigite) may also have initiated the foundering of a central caldera block. Such an event may have caused additional magma mingling and mixing. Heat transfer from the basic magma would cause extreme vesiculation of any unmixed silicic magma still present within the chamber, resulting in the intrusion of magma along ring-fractures and surface venting.

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9.8.4 The Eastern Red Hills Intrusive Centre (ERHIC)

9.8.4.1 Introduction

The Eastern Red Hills Intrusive Centre (ERHIC) (Figure 9-155; Figure 9-156) is the last of the four recognised foci of sub-volcanic activity of Skye Central Complex and occupies the ground between Loch Ainort in the NW, and Heaste in the SE.

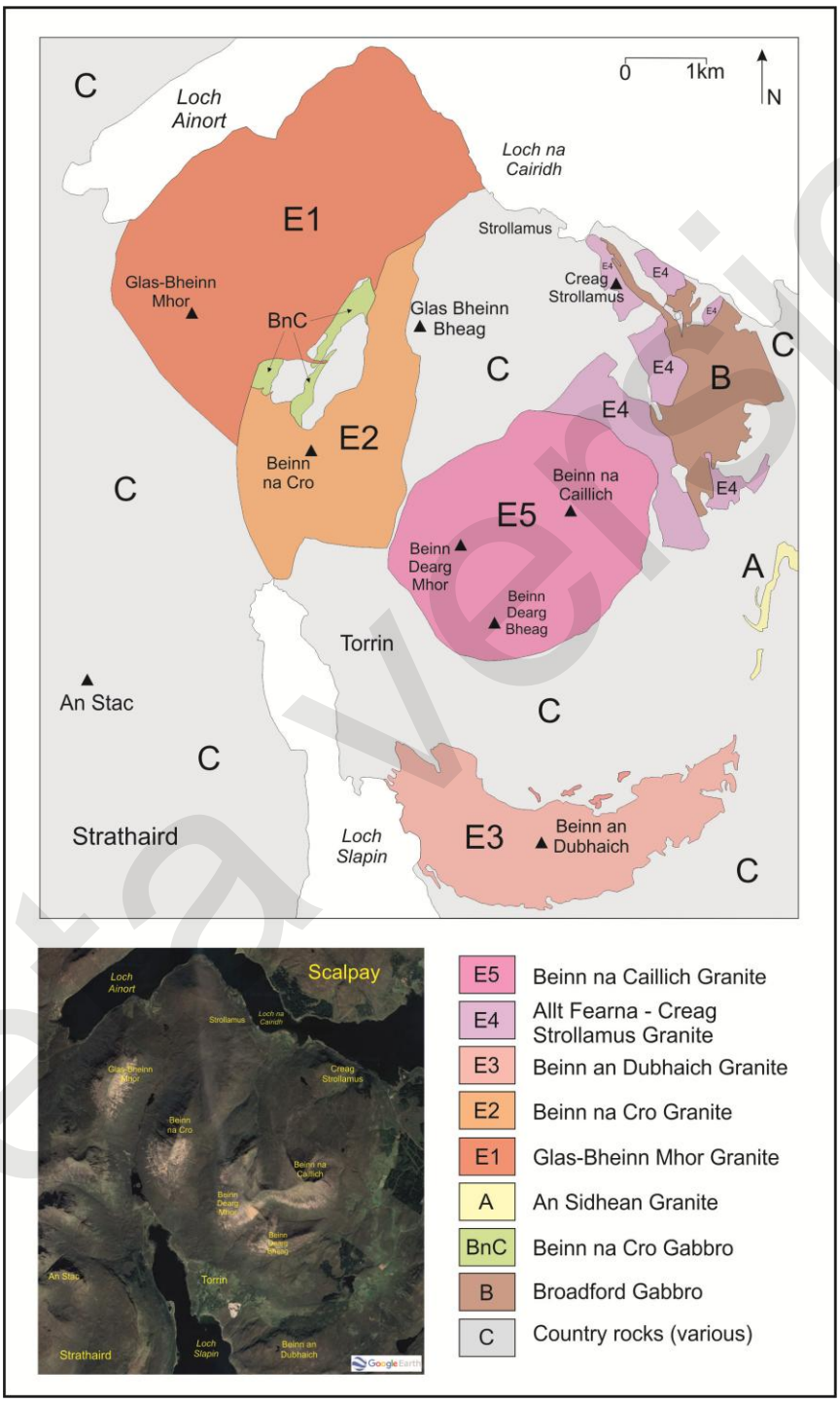


Figure 9-155: Lithodemic units of the Eastern Red Hills Intrusive Centre (ERHIC) (based on BGS (2005) and Emeleus & Bell (2005)), and Google Earth© image of the same area.

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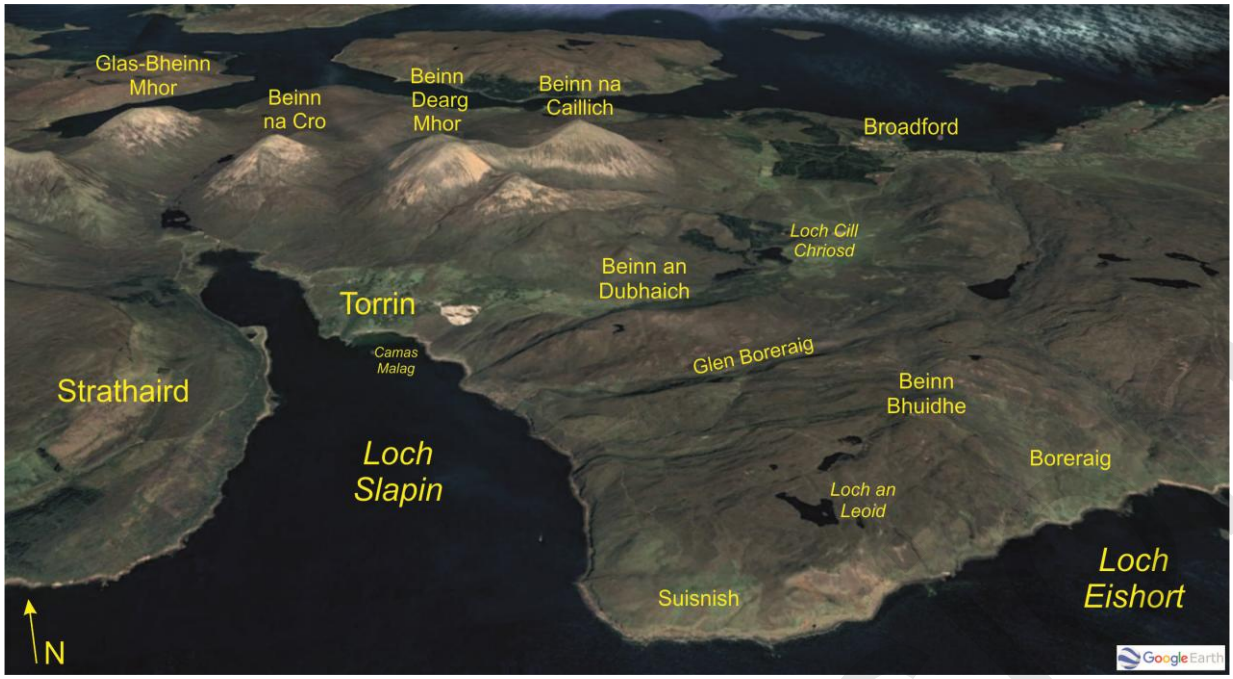


Figure 9-156: Oblique Google Earth© image of the Eastern Red Hills district, SW of Broadford. View towards the north.

The presence of a distinct intrusive centre in the area around Beinn na Caillich (now defined here as the Eastern Red Hills Intrusive Centre) was considered likely by Harker (1904), although he did not define in detail the various components. Further thoughts on the validity of an Eastern Red Hills Intrusive Centre were presented by Richey (1932), who defined an 'outer ring granophyre', composed of the granites exposed on Beinn na Crò and Beinn an Dubhaich, which surround the boss-shaped 'central mass' of Beinn na Caillich, also composed of granite. Richey also drew attention to a large suite of composite sills that form an incomplete arcuate belt, co-focal to the granite of Beinn na Caillich.

Subsequently, Stewart (1965) presented details of the time-relationships of the various units. Similar to the Western Red Hills Intrusive Centre (see above), unlayered gabbros pre-date the granites, although in this case an additional early intrusion is the Kilchrist Ring-dyke, formed by magma mingling/mixing. At a later stage, the large subvolcanic granites of the district were emplaced, followed by a suite of composite sills and dykes.

J.D. Bell (Bell 1976) outlined the time-relationships of the rock-units of the intrusive centre and the following table is modified from that work:

INTRUSIVE EVENTS	PRINCIPAL ROCK-TYPE
[YOUNGEST]	
dykes	Vitrophyre (‘pitchstone’), felsite, dolerite, peridotite
Composite sills and dykes	granophyre, felsite, basalt, hybrid lithologies
Beinn na Caillich Granite	amphibole, biotite granite/granophyre, felsite
Beinn na Crò & Beinn an Dubhaich granites	amphibole, biotite granite/granophyre, felsite
Glas-Bheinn Mhòr Granite	amphibole, biotite granite/granophyre, felsite
Broadford Gabbro	gabbro (altered)
Beinn na Crò Gabbro	olivine gabbro/bytownite gabbro
Kilchrist Ring-dyke	mixed-magma (basaltic-silicic) hybrid lithologies
[OLDEST]	

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9.8.4.2 The Kilchrist Ring-dyke

The Kilchrist Hybrids constitute five discrete outcrops of intrusive material in the area between Loch Cill Chriosd (Kilchrist) and Torrin, in Strath, and were first described by Harker (1896) (Figure 9-157; Figure 9-158). Three of these, the Eastern, Western and Southern intrusions, have the form an incomplete ring-dyke that surrounds various pyroclastic and volcaniclastic rocks (Chapter 6); exterior to the ring-dyke are country-rock Cambro-Ordovician and Jurassic sedimentary rocks (Chapters 2 and 3). The contacts of these three intrusions against the country-rocks dip steeply outwards, whereas the inner contacts against the pyroclastic and volcaniclastic rocks are relatively flat-lying and comprise fine-grained silicic material. The other two intrusions form steep-sided outcrops within the pyroclastic and volcaniclastic rocks and are referred to as the Cnoc nam Fitheach and Coire Forsaidh intrusions. Only the Eastern, Cnoc nam Fitheach and Coire Forsaidh intrusions form prominent topographic features; the first of which crops out on Creagan Fitheach, whereas the last two are exposed in the areas defined by their names. The relationships of the Eastern, Western and Southern intrusions, which are possibly (laterally) connected at depth, to those of Cnoc nam Fitheach and Coire Forsaidh, are obscure. The latter two masses do not appear to be related to a ring-dyke structure and may simply be discrete masses of the same material intruded into the central block of clastic rocks.

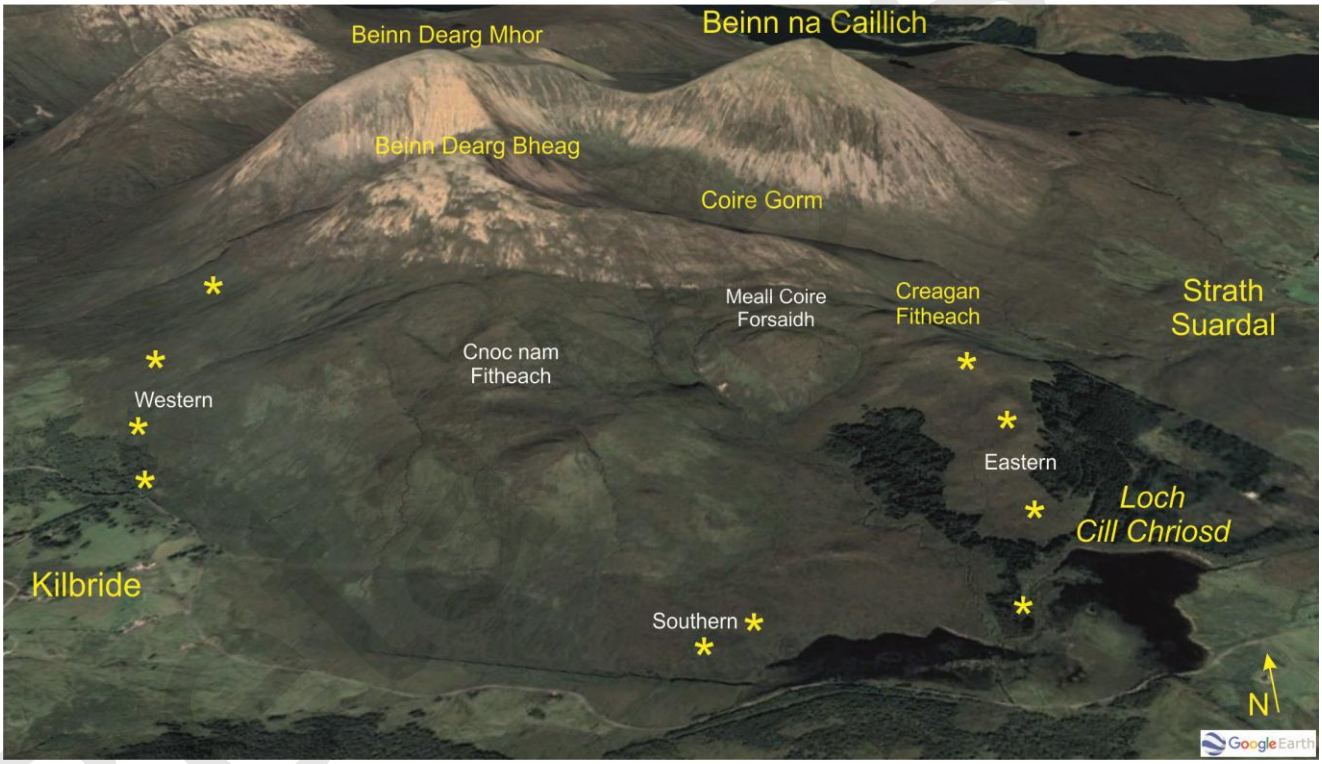


Figure 9-157: Oblique Google Earth© image of the area south of the Beinn na Caillich, between Strath Suardal and Kilbride, indicating the locations of the various parts of the Kilchrist Ring-dyke (*). View towards the north.

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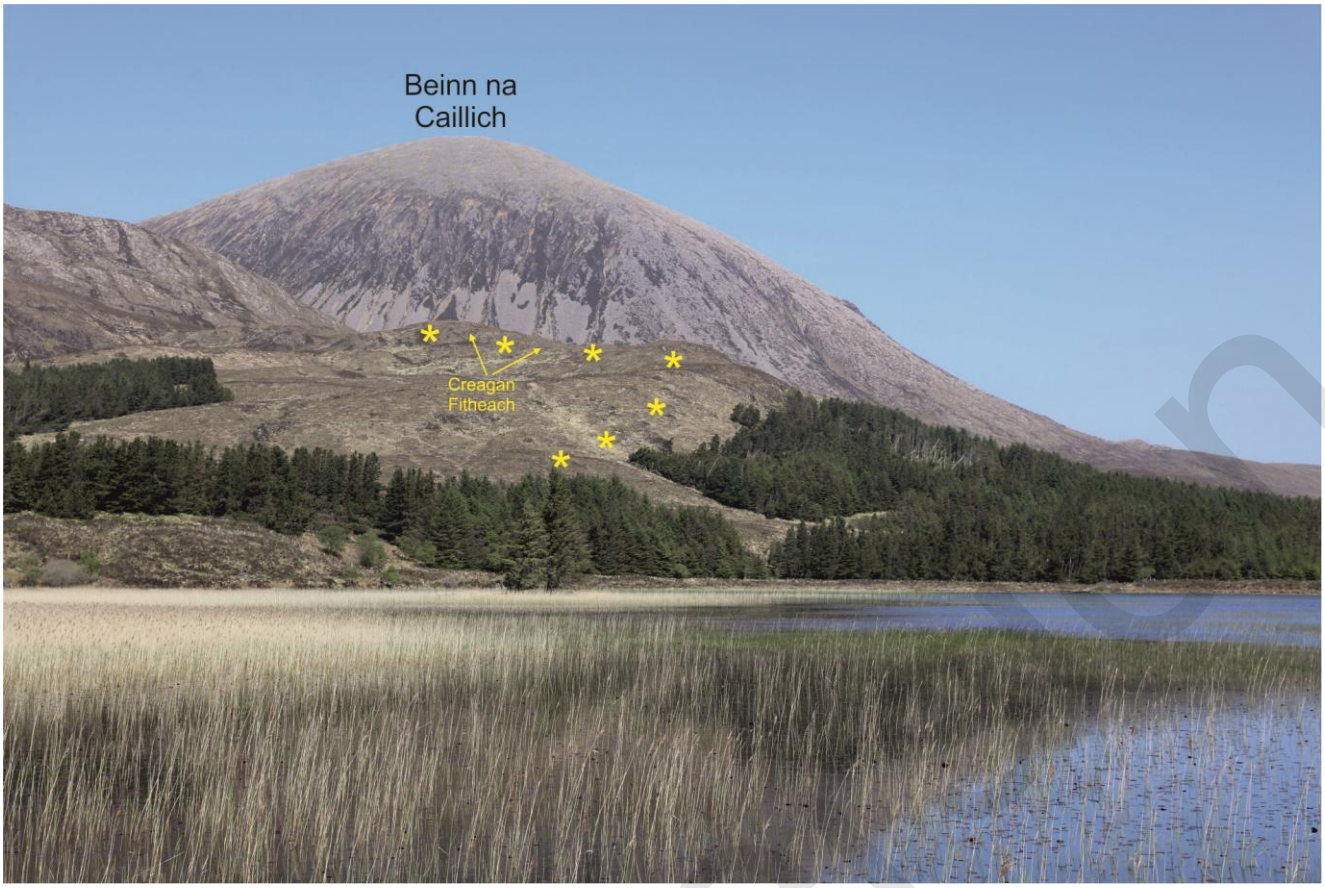


Figure 9-158: The surface expression of the Eastern outcrop of the Kilchrist Ring-dyke, forming the ridge of Creagan Fitheach, north of Loch Cill Chriosd. In the distance is Beinn na Caillich, composed of part of the Beinn na Caillich Granite. View is towards the north from Loch Cill Chriosd.

The hybrid (mixed-magma) origin of the Kilchrist Ring-dyke is readily noted in the field. Particularly obvious in this leucocratic to mesocratic, medium-grained rock are anhedral crystals of quartz (2–4 mm) fringed by clusters of amphibole and/or pyroxene, together with slightly larger (3–5 mm), rounded crystals of white (altered) alkali feldspar. Also present are larger (up to 3 cm) inclusions of fine-grained basic material with irregular and commonly diffuse margins (Figure 9-159), similar in many respects to the inclusions present within the Glamaig Granite of the WRHIC (see above).

These hybrid rocks are also similar to the mixed-magma/hybrid rocks of the Marscoite Suite of the WRHIC (see above), formed by the incomplete mixing (mingling) of basic and porphyritic silicic magmas, resulting in a hybrid magma in which the phenocrysts are out of equilibrium, hence their textural features. Unlike the rocks of the Marscoite Suite, no basic and silicic rocks occur in obvious close spatial or temporal association with the Kilchrist Hybrids. However, narrow, flow-banded, marginal facies, some of which have compositions more silicic than the typical Kilchrist Hybrids, occur, for example, in one of the tributaries of the Allt Coire Forsaidh, along the inner margin of the Eastern Intrusion (Figure 9-159). This material may have been intruded prior to the main mixed-magma ring-dyke and represent some of the silicic parent involved in the mixing process. Also present within these fine-grained facies are fragments of the pyroclastic and volcaniclastic material, most likely entrained from the material interior to the ring-dyke.



Figure 9-159: (a) Silicic (pale) and basaltic/mafic (dark) components of the Creagan Fitheach portion of the Kilchrist Ring-dyke north of Loch Loch Cill Chriosd (Kilchrist), coin *ca.* 24 mm across; and, (b) inner chill facies of the Eastern Intrusion of the Kilchrist Ring-dyke in the Allt Coire Forsaidh, SW of Creagan Fitheach, coin *ca.* 24 mm across.

Based on general field relationships, although no definite contacts are visible, the Kilchrist Ring-dyke may pre-date the late-stage Beinn na Caillich Granite (see below) and constitutes a small, discrete, sub-volcanic centre that pre-dates the granite-dominated ERHIC (*s.s.*).

9.8.4.3 The Beinn na Crò Gabbro

The Beinn na Crò Gabbro is a coarse-grained, unlayered, basic intrusion with tholeiitic affinities, varying in composition between an olivine-poor gabbro and an olivine-rich bytownite gabbro. It consists of several thick sheets of relatively flat-lying material intruded into basaltic lavas along the N-S -trending ridge of Beinn na Crò. The Glas-Bheinn Mhòr Granite (see below) has subsequently intruded and altered both the gabbro and the lavas, and it is not, therefore, possible to determine the original extent of either unit.

The gabbro is exposed in the deep gullies NW of the summit of Beinn na Crò, where the complex sheet-like inter-relationships between the gabbro, lavas and granite are discernible. Also present are numerous basic dykes that intrude the lavas and the gabbro, but predate the Glas-Bheinn Mhòr Granite (Figure 9-160).

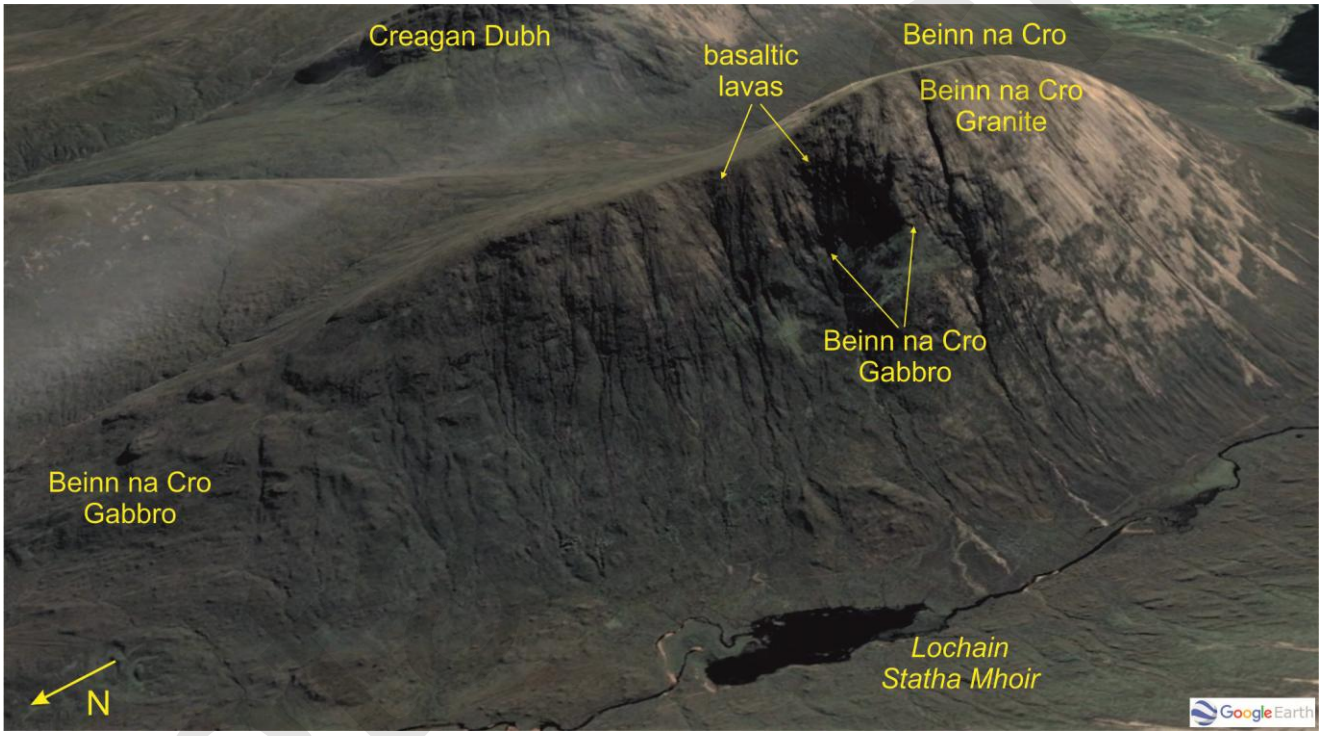


Figure 9-160: Oblique Google Earth© image showing the Beinn na Crò Gabbro and country-rock basaltic lavas. View towards the SE.

9.8.4.4 The Broadford Gabbro

The Broadford Gabbro crops out over an area of *ca.* 3 km^2, WNW of Broadford (Figure 9-155). Along its eastern margin it is bound by Cambro-Ordovician and Jurassic strata, the latter in a faulted relationship, whereas further west the gabbro is cut by younger granites. In the area around Creag Strollamus, the field relationships are complicated by the presence of the Kishorn Thrust Plane (Chapter 2) and, consequently, there is some doubt about the shape of the intrusion (see below).

Harker (1904) mapped the area in detail and concluded that the gabbro is intimately associated with Cambro-Ordovician Durness Group dolostones (Chapter 2) that crop out east of the Kishorn Thrust Plane.

Throughout its exposure, the gabbro contains numerous small (typically less than 50 m across) enclosures of the carbonates, which form small topographic depressions within the harder igneous rock. Harker (1904) concluded that the intrusion is boss-shaped, with steeply inclined margins. In contrast, King (1953a) and Bailey (1954a) suggested that the gabbro is most likely sheet-like.

Along the northern slopes of Creag Strollamus, the gabbro extends to the NW as a dyke-like mass with a width of *ca.* 200 m (Figure 9-161). This elongate part of the intrusion tapers NW of Creag Strollamus but does not reach the coast. Towards the margins of the intrusion there are doleritic and basaltic facies. The common presence of 'acidified' and 'granite-veined' facies suggested to King (1953a) that some form of hybridisation process had taken place between the gabbro and younger granites.



Figure 9-161: Profile of the dyke-like portion of the Creag Strollamus Gabbro on the NW side of Creag Strollamus, viewed towards the NE.

The Broadford Gabbro is an unlayered, medium- to coarse-grained rock composed of clinopyroxene and zoned plagioclase in an ophitic to sub-ophitic arrangement (Figure 9-162). Unlike the gabbros of the Cuillin Intrusive Centre, olivine is not present. Local variations in the modal percentages of the two dominant minerals give rise to pyroxene- and plagioclase-rich facies. In general, the gabbro has been severely hydrothermally altered by the nearby younger granites, with the resultant development of secondary mineral assemblages. Commonly, pyroxene is replaced by aggregates of amphibole + chlorite + epidote. Marginal facies of the intrusion locally show the development of shearing and brecciation, possibly due to volatile release during intrusion.

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Figure 9-162: Typical Broadford Gabbro, with dark aggregates of amphibole, chlorite and epidote replacing original clinopyroxene and white plagioclase. Coin *ca.* 24 mm across.

A possible mechanism of intrusion for the Broadford Gabbro that alleviates the 'space problem' and provides a plausible way of explaining the complex relationships between the gabbro and the enclosures of Cambro-Ordovician dolostone, is that basaltic magma was (to some extent) intruded into limestone voids or caves, which had developed at some previous stage. A similar explanation may be appropriate to explain some of the complex field relationships of the Beinn an Dubhaich Granite (see below).

9.8.4.5 The Glas-Bheinn Mhòr Granite (E1)

The Glas-Bheinn Mhòr Granite is the first of the large sub-volcanic silicic intrusions of the ERHIC (*s.s.*). It crops out on the hill of that name and clearly crosscuts members of the older WRHIC (for example, the Loch Ainort Granite and the Marscoite Suite, see above) (Figure 9-163). The eastward extent of this granite has not been determined in detail, although it certainly crops out on the low ground west of the Beinn na Crò ridge. Its outer (western) margin is steeply inclined, dipping to the west, and can be traced from Sròn Ard a' Mhullaich, at the head of Loch Ainort, south to the col between Belig and Glas-Bheinn Mhòr (Bell 1966).

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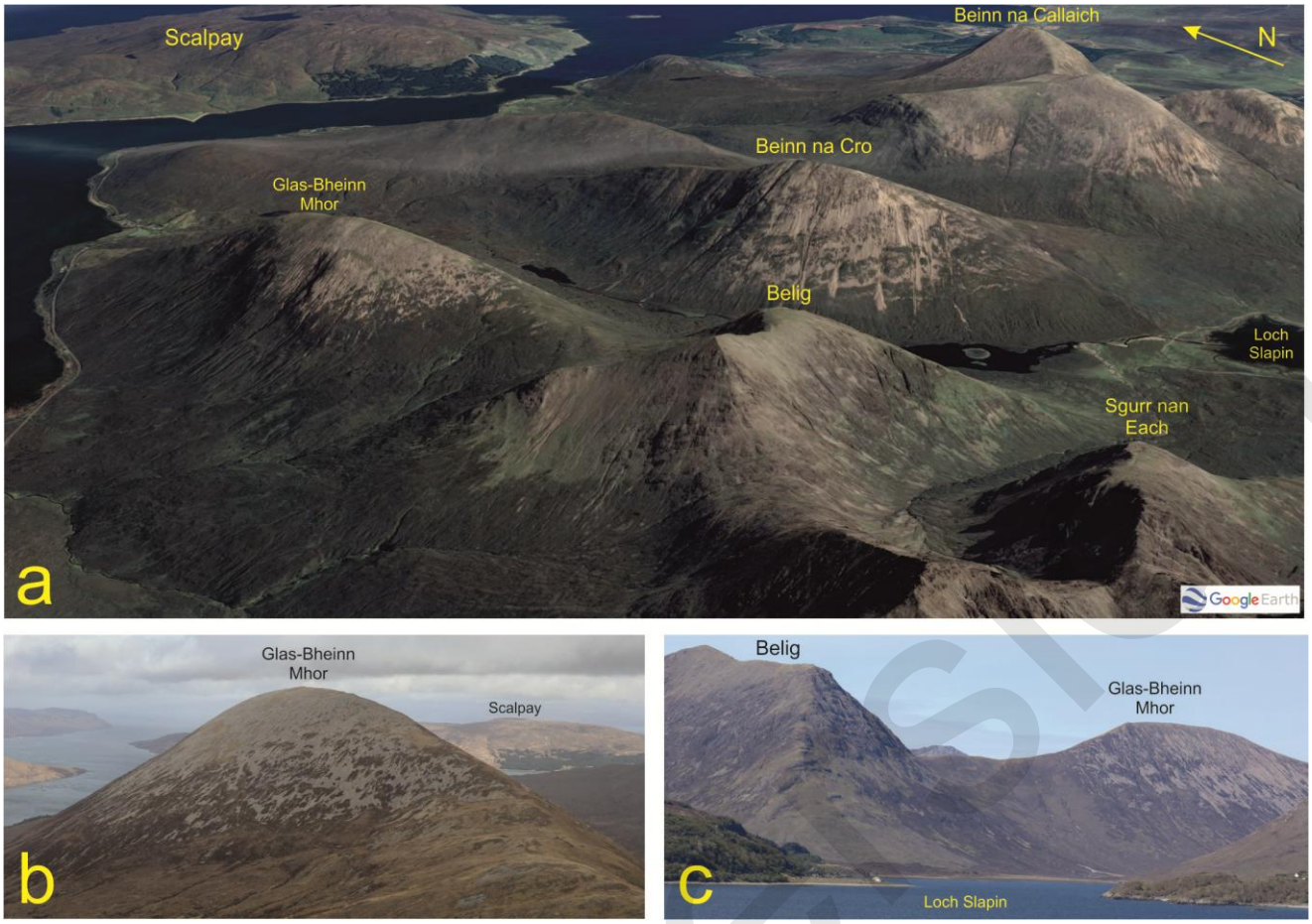


Figure 9-163: (a) Oblique Google Earth© image illustrating the location of the Glas-Bheinn Mhòr ridge, which is essentially the outcrop of the Glas-Bheinn Mhòr Granite; (b) the Glas-Bheinn Mhòr ridge, view towards NNE; and, (c) Glas-Bheinn Mhòr from the east side of Loch Slapin, view towards the NW.

In hand-specimen, the Glas-Bheinn Mhòr Granite weathers dull grey and is distinctly porphyritic, with phenocrysts of normally zoned plagioclase ($An_{20–27}$, Bell 1966) set in a fine-grained groundmass that is composed of a granophyric intergrowth of quartz and alkali feldspar. The dominant mafic minerals are amphibole and brown mica, although primary pyroxene, commonly replaced by secondary amphibole, is recognised (Bell 1966). Accessory apatite, zircon, titanite, Fe-Ti oxides and fluorite are also present.

Irregularly dispersed throughout the intrusion are small clots of mafic minerals, dominated by amphibole, brown mica and Fe-Ti oxides. These most likely represent partially digested inclusions of mafic material, a feature of other granites within the Skye Central Complex and discussed elsewhere in Chapter 9.

9.8.4.6 The Outer Granites (E2, E3 & E4)

The outer granites of the ERHIC are defined here as consisting of the various coarse-grained silicic intrusions that crop out in the arcuate belt which runs from Beinn na Crò in the west, south to Beinn an Dubhaich, and thence around the eastern side of Beinn na Caillich to the Allt Fearna - Creag Strollamus area (Figure 9-155). These separate granite outcrops were tentatively grouped together by Richey (1932) and subsequent work by Stewart (1965) and Bell (1982) confirm this interpretation. These intrusions are slightly porphyritic, with uncommon phenocrysts of alkali feldspar and quartz, and contain hornblende and biotite. Depending upon the amounts of these ferromagnesian minerals, both grey and reddish-brown

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weathered surfaces occur. The country-rocks that host the different parts of this annular-shaped group of intrusions span a wide range in terms of lithology and age.

Formally, the three main intrusions are: (a) Beinn na Crò; (b) Beinn an Dubhaich; and, (c) Allt Feàrna - Creag Strollamus.

(a) Beinn na Crò Intrusion (E2): has a steep, outer contact against the older Glas-Bheinn Mhòr Granite (see above) and an almost vertical contact against a screen of fragmental rocks and rhyolitic lavas on the east side of Srath Beag, that separates it from the younger Beinn na Caillich Granite (see below) (Figure 9-155; Figure 9-164).

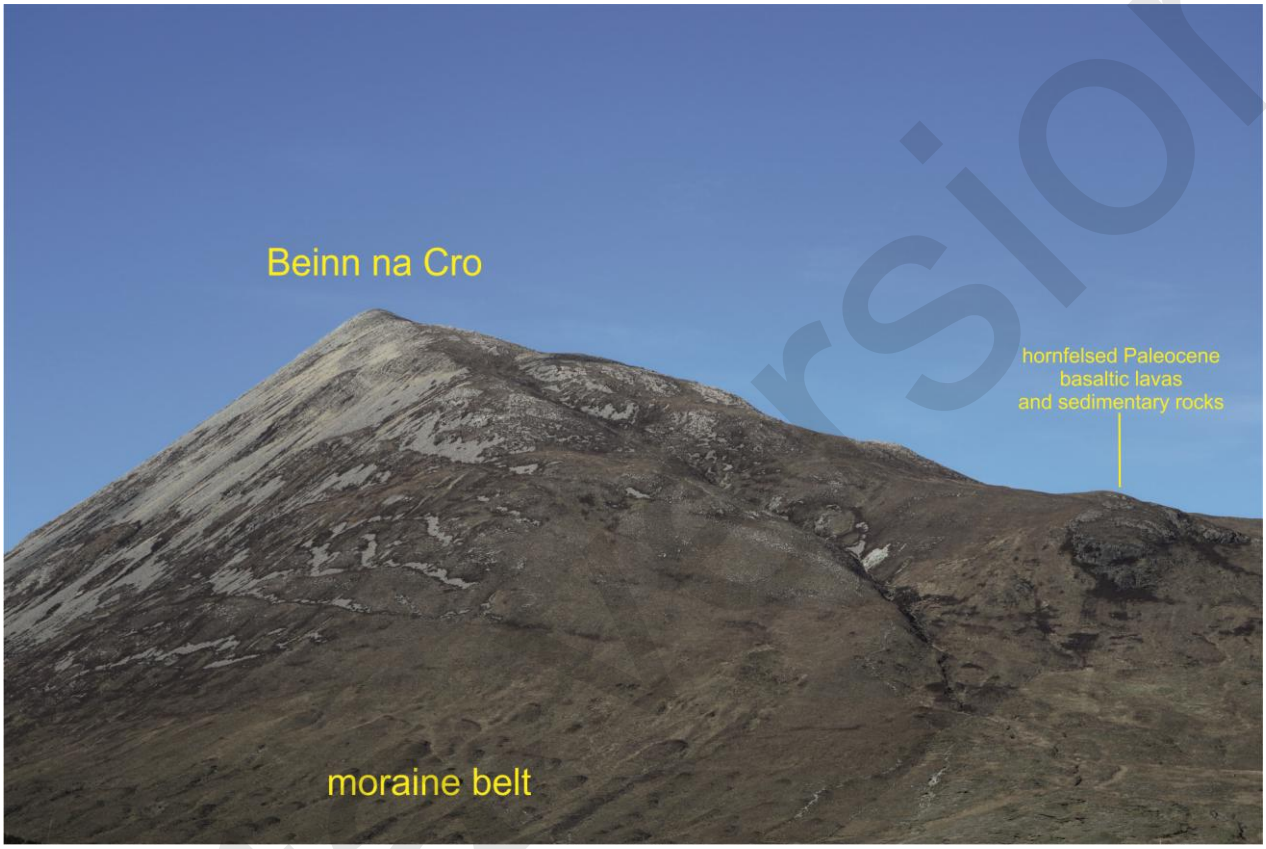


Figure 9-164: Beinn na Crò from the west side of Loch Slapin, composed mainly of the Beinn na Crò Granite, here in contact with hornfelsed country-rock basaltic lavas and interbedded sedimentary units. View towards the north.

(b) Beinn an Dubhaich Intrusion (E3): a much-studied granite that is wholly intruded into a broad anticline of Cambro-Ordovician Durness Group dolostones (Chapter 2) on the east side of Loch Slapin (Figure 9-165). Formation of the anticline predominantly pre-dates intrusion of the granite. The outcrop of the intrusion is significantly complicated by numerous enclosures of the country-rock dolostones (Figure 9-166). There is little evidence of stoping or tectonic disturbance associated with the intrusion of this granite. Older (Paleocene) dykes that cut the large enclosures of country-rock dolostones show little sign of deviation from the regional (NW-SE) trend (Chapter 7). Local variations in the attitude of the granite - country-rock contact(s) have led to different interpretations being suggested for the general shape of the Beinn an Dubhaich Granite. Harker (1904) suggested that it was a steep-sided mass, and similar conclusions have been reached by Stewart (1965), Raybould (1973) and Bell (1982). In contrast, King (1960) and Whitten 1961b) favour a sheet-like structure, intruded along the Kishorn Thrust Plane, dipping at a shallow angle to the SE (Chapter 2). With the first interpretation, the enclosures of Cambro-Ordovician

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dolostone represent roof-pendants, whereas those who favour the sheet-like model suggest the dolostone enclosures represent irregularities in the Cambro-Ordovician 'floor', which lies below the base of the granite sheet. A drill hole through one of these enclosures of country-rock (reported by Raybould 1973) encountered granite below, which adds support to the 'steep-sided contact' model. Hoersch (1979), based on a ground magnetometer study, concluded that the intrusion is a steep-sided stock and extends to depth. Hoersch (1979) also suggested that lobes of the granite penetrate the area to the north. One other emplacement model worthy of consideration is that the granite's shape is, in part, due to the emplacement of magma into voids of a previously formed cave system, a present-day feature of the Cambro-Ordovician dolostones and, by inference, a feature prior to the emplacement of the granite.

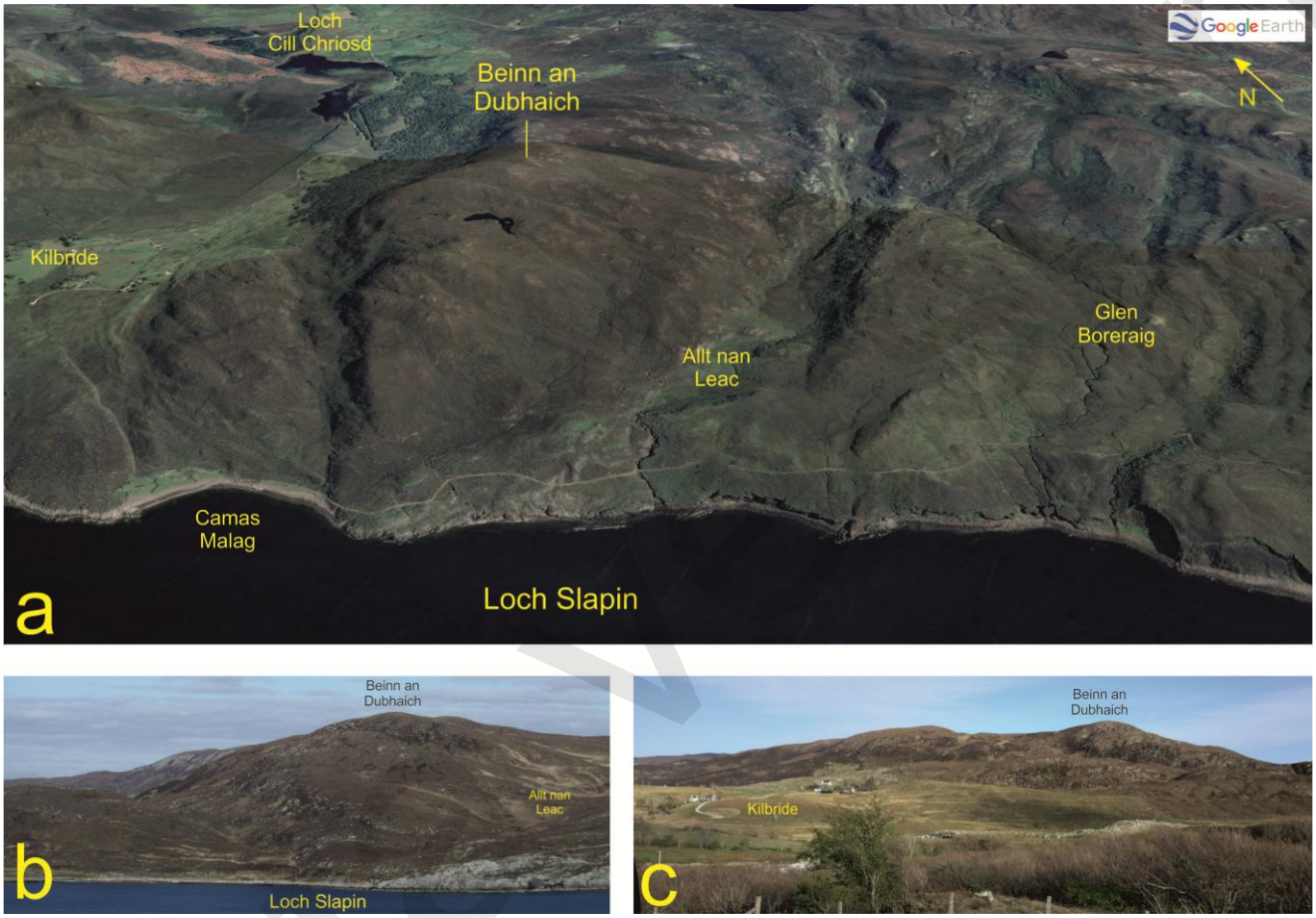


Figure 9-165: (a) Oblique Google Earth© image of the E-W -trending Beinn an Dubhaich ridge viewed from the east side of Loch Slapin, with the granite forming the higher, dark, heather-clad ground, view towards the east; (b) Beinn an Dubhaich Granite (E3), with the more verdant lower ground comprising Cambro-Ordovician Durness Group dolostones to the north (left) and Jurassic strata to the south (right), view towards the east; and, (c) Beinn an Dubhaich Granite (E3) forming the dark, heather-covered, high ground, with the more verdant lower ground at Kilbride comprising Cambro-Ordovician Durness Group dolostones, view towards the south.

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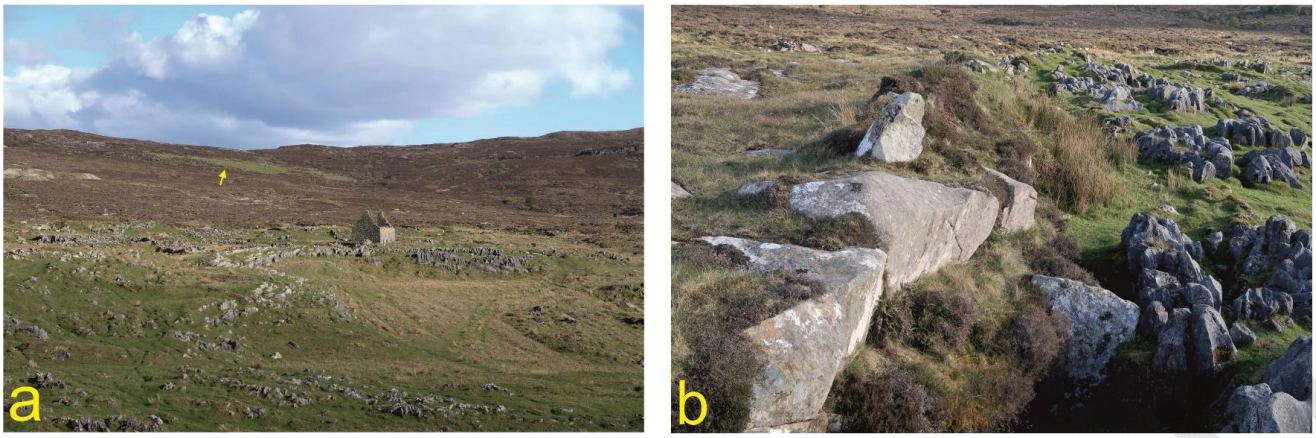


Figure 9-166: (a) The margin of the Beinn an Dubhaich Granite (E3) at the old Manse at Kilchrist, SE of Loch Cill Chriosd, with the contrasting heather-dominated ground of the granite and the grass-dominated ground of the Cambro-Ordovician Durness Group dolostones, enclosure of dolostones in the far distance (arrowed), view towards the SW; and, (b) detail of granite (left) – dolostone (right) contact close to the old Manse at Kilchrist.

Tilley (1949) records the presence, locally, of alkali pyroxene -bearing marginal facies of the Beinn an Dubhaich Granite, associated with the development of contact skarns in the dolostone country-rocks and Raybould (1973) identifies four distinct varieties of granite within the intrusion, namely: porphyritic microgranite, granophyre, pale green granite, and hornblende granite. Tuttle & Keith (1954) and Tuttle & Bowen (1958) investigated the inversion temperatures of quartz and feldspar crystals from the intrusion and concluded that, during crystallisation, high-temperature features had been 'quenched-in', such as would be expected if the granite had crystallised from a rhyolitic magma and had not been formed by lower-temperature metasomatic processes. The thermal and metasomatic effects of this granite on the surrounding country-rocks are outlined below.

(c) Allt Feàrna - Creag Strollamus Intrusion (E4): consists of several small granite, microgranite and porphyritic felsite intrusions/outcrops that intrude various pre-Paleocene country-rocks, as well as the older Broadford Gabbro (see above) (Figure 9-167). The boundaries of these masses are complicated by the presence of the Kishorn Thrust Plane, which dips at a shallow angle towards the east. Harker (1904) and King (1953a) note that, locally, granite has been intruded along the thrust plane. King (1953a) further suggests that much of the granite formed by *in situ* metasomatic replacement of original Torridonian strata (Chapter 2), but this hypothesis was rejected by Stewert (1965) on several grounds, but principally because of vertical contacts between the granite, the Broadford Gabbro and Cambro-Ordovician dolostones, as seen in tributaries of the Allt Feàrna. Where granite and gabbro are in contact, zones of hybrid material have developed. The contact between the main intrusion of this granite (in the Allt Feàrna - Creag Strollamus area) and the Beinn na Caillich Granite (see below) may be traced from Buaile nan Aodan (SE of Beinn na Caillich), towards the plateau area around Lochain Beinn na Caillich, where it follows the sharp break in slope at *ca*. 250 m OD, west to Creagan Dubh. This change in slope provides the most useful field evidence as to the position of the boundary between these two granites. The Beinn na Caillich Granite (see below) is commonly chilled against the older granite, thereby allowing the contact to be readily distinguished.

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Figure 9-167: Typical rusty-brown -weathering Creag Strollamus (Granite) Intrusion on the east side of Creag Strollamus. Pole *ca.* 1 m long. View towards the north.

The irregularly shaped silicic intrusion that crops out at An Sithean/Sidhean, SSW of Broadford, is part of the suite of outer granite intrusions and is, in places, extremely fine-grained, essentially a porphyritic felsite.

9.8.4.7 The Beinn na Caillich Granite (E5)

The Beinn na Caillich Granite is interpreted as the youngest of the large sub-volcanic intrusions of the ERHIC and crops out on the three prominent summits WSW of Broadford, Beinn na Caillich, Beinn Dearg Mhòr and Beinn Dearg Bheag (Figure 9-155; Figure 9-168; Figure 9-169; Figure 9-170). This intrusion has a near-perfect circular outline, although somewhat linear at Creagan Dubh, north of Beinn Dearg Mhòr (Figure 9-171). The contact of the Beinn na Caillich Granite with the surrounding country-rocks is typically steep and there is commonly the development of a fine-grained chill facies. Along its western, southern and eastern margins, the granite has intruded various pyroclastic and volcaniclastic rocks, whereas to the north it is in contact with basaltic lavas, and to the NE with the Creag Strollamus (Granite) Intrusion (see above).

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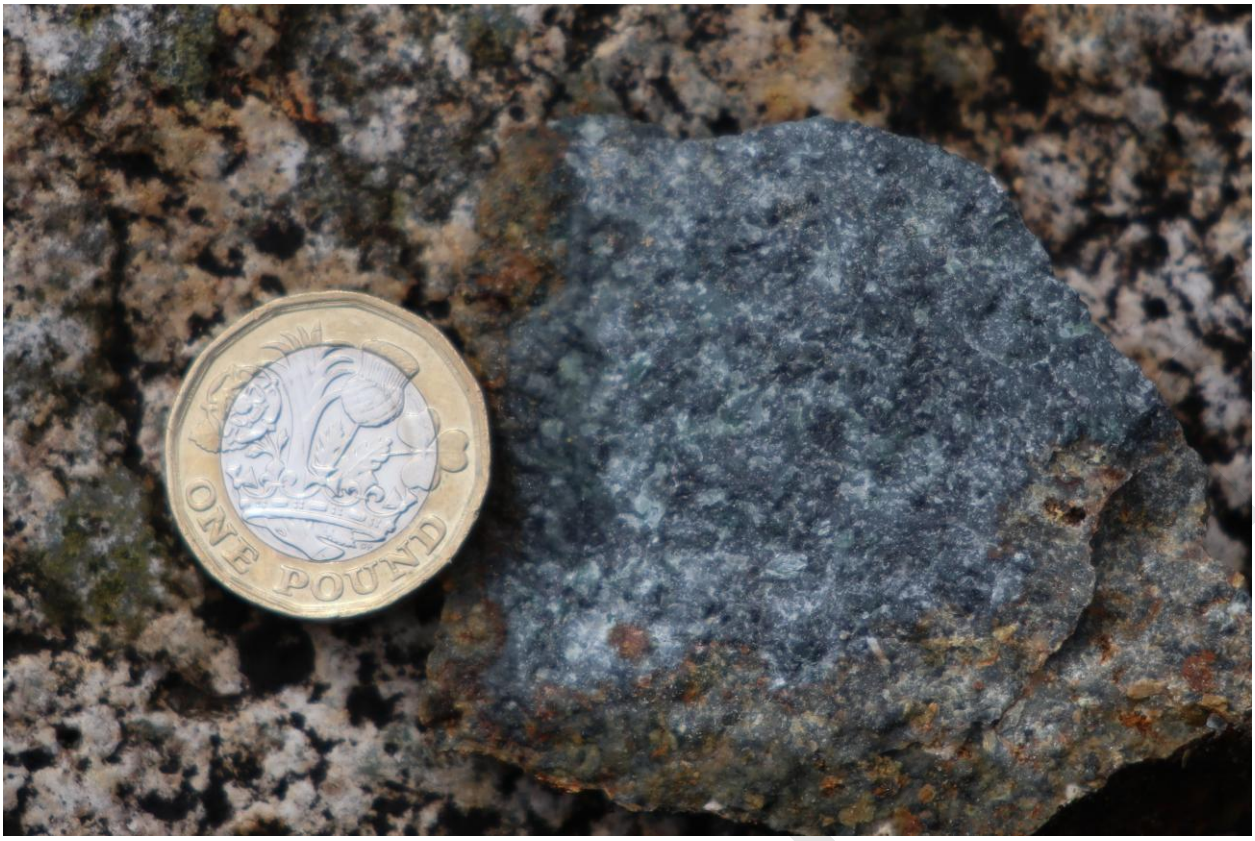


Figure 9-168: Fresh surface of the Beinn na Caillich Granite, contrasting with the typical weathered appearance. Coin *ca.* 24 mm across.

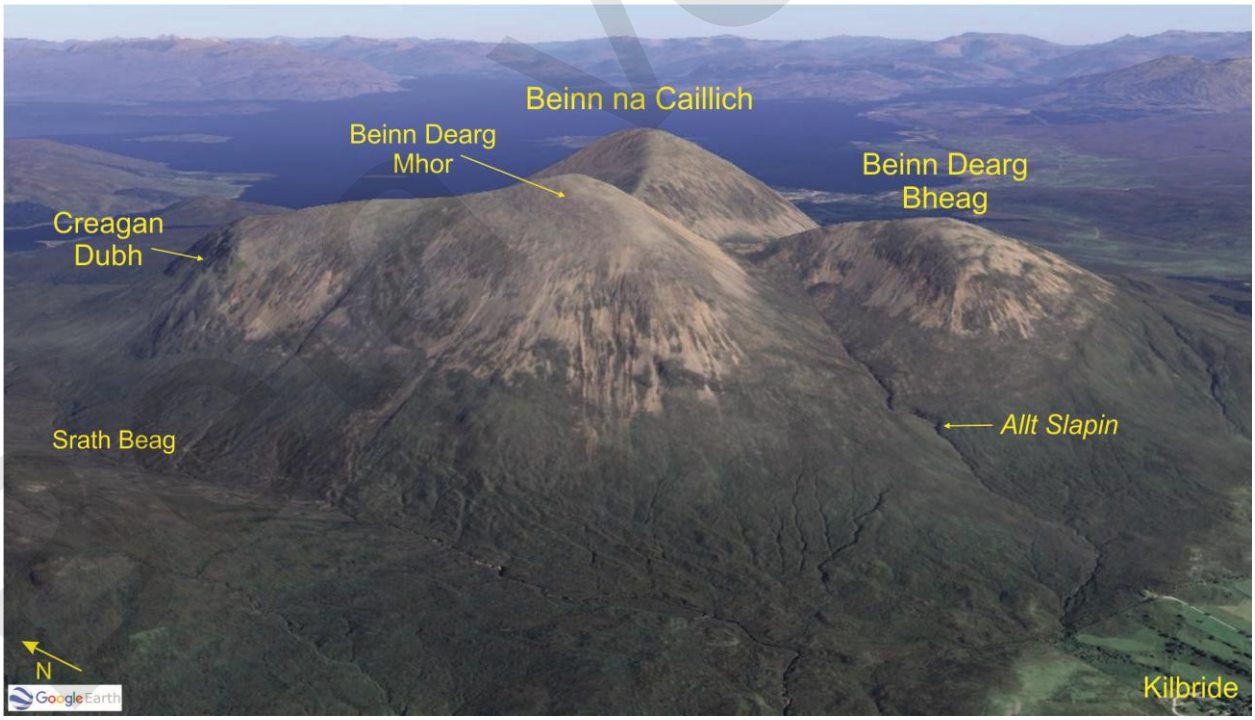


Figure 9-169: Oblique Google Earth© image of the three summits, Beinn Dearg Mhòr (left), Beinn na Caillich (far centre) and Beinn Dearg Bheag (right), which constitute most of the outcrop of the Beinn na Caillich Granite. View is towards the NE.



Figure 9-170: The arête separating Coire Gorm (left) and Coire Reidh (right) in the Beinn na Caillich Granite. View is towards the SW to Beinn Dearg Mhòr and, beyond, Blà Bheinn.



Figure 9-171: The linear NW margin of the pale Beinn na Caillich Granite in Coire Garbh against basaltic lavas forming Creagan Dubh. View from Creag Strollamus, towards the SW.

Breccia facies due to late-stage volatile release are locally developed and which, when weathered, are very distinctive (Figure 9-172). Miarolitic cavities are another common feature of this intrusion and are particularly well-developed in the summit areas of the three hills noted above, presumably because they

are relatively close to the roof zone of the intrusion. Within these cavities are euhedral crystals of quartz, alkali feldspar and, uncommonly, fluorite.



Figure 9-172: Localised development of brecciated Beinn na Caillich Granite. Loose block at Bealach Coire Sgreamhach, between Beinn Dearg Mhòr and Beinn Dearg Bheag. Pole *ca.* 1 m long.

Two mineralogical facies of the granite are readily identified in the field. First, a normal, coarse-grained facies, consisting of phenocrysts (3–5 mm) of quartz and alkali feldspar, set in a groundmass that is dominated by the development of a granophyric intergrowth involving the same two minerals. The alkali feldspar is generally clouded. Also present are laths of oligoclase ($An_{20–25}$). The main ferromagnesian minerals are hornblende and biotite, commonly occurring as small clusters associated with Fe-Ti oxides. Zircon, titanite and apatite are present as accessory minerals. The fine-grained chill facies of the intrusion is only exposed locally and typically does not exceed 5 m in width; it is most easily examined in the gorge at the head of the Allt Slapin, north of Torrin, where the stream cuts through the contact between the granite and various breccias. This marginal facies is a felsite which, locally, veins the country-rocks. Extreme chilling against the country-rocks has led to the development of spherulitic masses (1–2 mm) composed of quartz and alkali feldspar set in a green felsitic (originally glassy) groundmass. The same feldspar phenocrysts as in the normal/dominant granite are present, although they are typically smaller (1–2 mm). The main ferromagnesian minerals are microphenocrysts (0.5–1 mm) of the Fe-rich clinopyroxene, ferrohedenbergite, and an almost pure Fe-olivine, fayalite. Alteration of the ferrohedenbergite to aggregates of chlorite, epidote and actinolite, and of the fayalite to serpentine and/or chlorite, are common.

The differences in the mafic mineral assemblages of the two facies of the granite (main and marginal) may be explained in terms of the bulk composition of the magma involved. Essentially, the silicic magma when intruded was close to its liquidus temperature, containing relatively few phenocrysts. Under such conditions, silicic magmas with low CaO contents and high Fe/Mg ratios will crystallise olivine and pyroxene in preference to hornblende and biotite. The volatile content/concentration will be low during

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the early stages of crystallisation. and this will further restrict or prevent the formation of hydroxyl-bearing minerals. Subsequent crystallisation will decrease the Fe/Mg ratio of the magma and increase its relative CaO and volatile contents, with hornblende and biotite becoming the stable ferromagnesian minerals.

9.8.4.8 The Composite sills

Composite sills and dykes constitute an important component of the ERHIC, cropping out over an arc at least 15 km long, from Rubha Suisnish in the south, to Rubha na Sgianadin in the north, and possibly continuing onto Scalpay (Figure 9-173). The radius of the circle, of which this arc forms almost a half, is *ca*. 5 km and is co-focal with the centre of the Beinn na Caillich Granite (see above), suggesting a close spatial (and genetic) relationship between the composite intrusions and the granite(s). These intrusions were first described in detail by Harker (1904), who noted over twenty discrete outcrops, all of which occur within strata of Lower Jurassic age (Chapter 3).

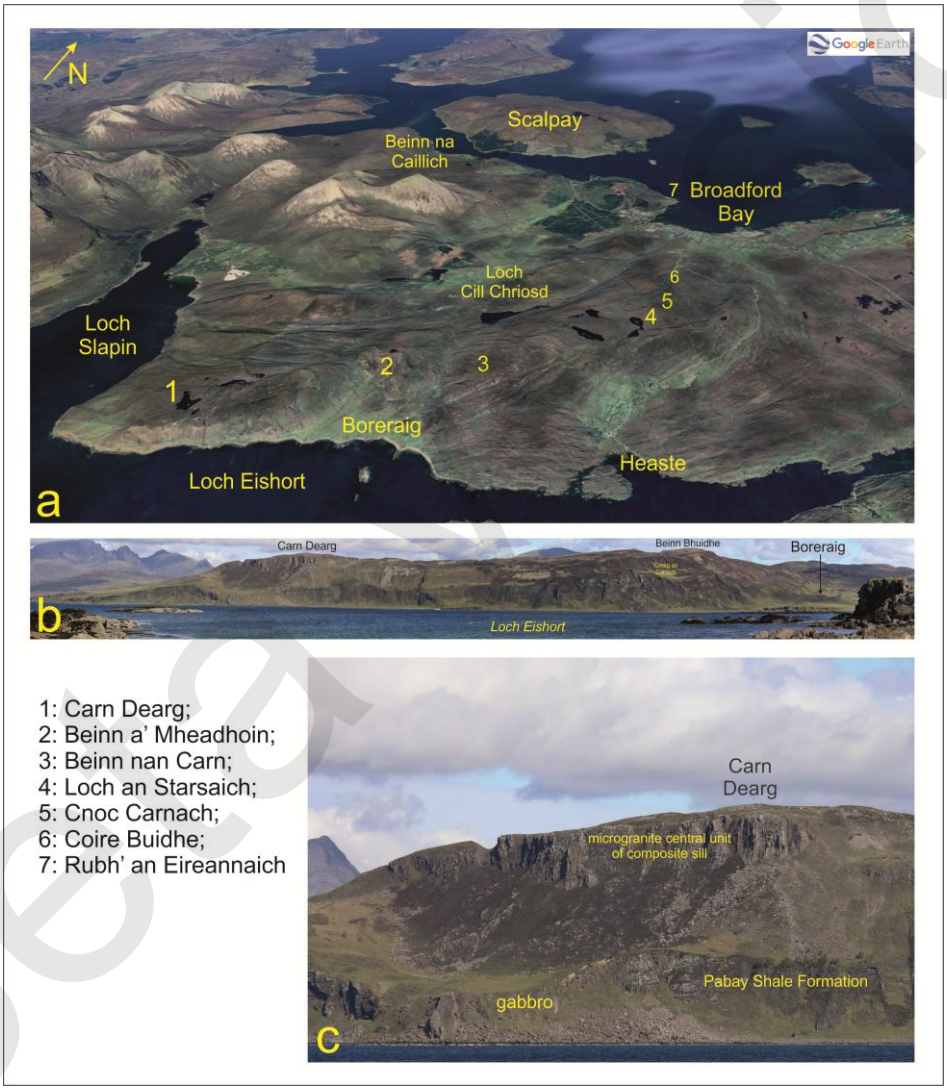


Figure 9-173: (a) Oblique Google Earth© image of Strath, indicating the (numbered) locations of the main composite sill outcrops; (b) coastal section on the north side of Loch Eishort between Càrn Dearg and Boreraig; and, (c) the composite sill of Càrn Dearg on the north side of Loch Eishort, with country-rock Lower Jurassic Pabay Shale Formation strata forming the coastal cliffs, together with a steep-sided gabbro intrusion that has produced much of the scree on the coast, view towards the NW from Ord.

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Harker (1904) identified various types of minor intrusions that are composed of silicic and basic components in close association. The suite of sills and dykes described here are referred to by Harker (1904) as being of the Cnoc Càrnach Type. They are typically composed of three distinct units: upper and lower basic portions that preserve evidence of chilling against the country-rock strata, and a central silicic portion (granophyre, microgranite or felsite) that shows no evidence of chilling against the fine-grained, basic material. All of the sills are either flat-lying, or dip at a shallow angle (*ca.* 15°) towards a point below Beinn na Caillich. The basic portions have thicknesses of 0.5–2.5 m, whereas the silicic centres have much greater thicknesses, commonly 50 m, or more. In many instances, erosion has removed the upper basic unit and the upper part of the silicic centre. For example, the sills that crop out on Càrn Dearg (Figure 9-173), Beinn nan Càrn and Cnoc Càrnoch, itself, are in part eroded down to this level. Numerous faults disrupt and complicate the (original) relatively simple field relationships of these intrusions.

Evidence for the intrusion of the silicic magma after the basic magma includes the presence of fragments of the latter within the former, together with veins of felsite and microgranite cutting the basic portions, for example, within the upper basic unit of the Cnoc Càrnach intrusion, along its western side.

The composite dykes associated with these sills may have acted as feeders. They have similar geometries, with marginal, fine-grained, basic portions flanking a thicker central silicic unit. Numerous examples of these dykes are preserved, with the intrusion at Loch Fada, north of Càrn Dearg, providing the most clear-cut evidence for the close genetic relationship between the dykes and the sills.

Formation of these intrusions has been determined from the petrography and whole-rock geochemistry of the *ca.* 5 m thick composite sill that crops out at Rubh' an Eirèannaich, on the west side of Broadford Bay (Figure 9-174) (Harker 1904; Buist 1959, Bell 1982, 1983; and Bell & Pankhurst 1993). The sill has upper and lower basaltic units (strictly of ferrobasaltic andesite composition), each 1.3–1.4 m thick, and a central porphyritic felsite/rhyolite (*ca.* 2.4 m thick). Whole-rock Sr-isotope data indicate that the basaltic magma was generated by fractional crystallisation of a more primitive, basic magma and has also been contaminated by crustal material, and that the felsite has a significant crustal component, i.e. produced by melting of continental crust. Unlike most of the composite sills, boundaries between the basaltic and silicic parts are completely gradational, typically over a distance of 10- 20 cm. The upper and lower contacts with the Lower Jurassic country-rock strata exhibit strong chilling, producing a glassy (now partially/totally devitrified) material. This grades over a few millimetres into a fine-grained, dark grey rock that contains phenocrysts of labradorite and xenocrysts of oligoclase (with rounded edges) and alkali feldspar (exhibiting the so-called fingerprint texture, indicating disequilibrium), all set in a groundmass dominated by augite, plagioclase (andesine-labradorite) and Fe-Ti oxides. The central portion of the sill is composed of light grey to greenish-white porphyritic felsite/rhyolite, with phenocrysts of oligoclase and rare alkali feldspar, set in a felsitic groundmass composed of recrystallised quartz and alkali feldspar. Between the contrasting basic and silicic rock-types, the 10-20 cm thick hybrid zones exhibit a complete compositional spectrum. Closest to the basic units, xenocrysts of oligoclase and alkali feldspar within the hybrid are set in a groundmass dominated by augite, plagioclase and Fe-Ti oxides. Towards the silicic centre of the sill, these minerals grade imperceptibly into phenocrysts (with no evidence of disequilibrium, such as rounding or magmatic corrosion), set in a felsitic groundmass.

Beta version



Figure 9-174: The composite sill at Rubh' an Eiréannaich on the west side of Broadford Bay. B: basaltic lower and upper units; S: silicic (microgranite) central unit; H: hybrid zone. View towards the south. Pole *ca.* 1 m long.

These features suggest that two periods of hybridisation of basic and silicic magmas have taken place. First, there was the incorporation of a silicic magma into a basic magma, within a deeper-level magma chamber, resulting in the partial resorption of phenocrysts that were present within the silicic magma. The rounded and corroded oligoclases and alkali feldspars within the basic portions of the composite sill represent this process in an arrested state. The absence of quartz xenocrysts within the basic units suggests that either quartz was not present as a phenocryst phase in the silicic magma, or that it was totally dissolved during the mixing. The compositionally transitional zones formed either by *in situ* hybridisation, by diffusion between the two contrasting magmas after their emplacement, or by mixing prior to or during emplacement. Any fractional crystallization of the unmixed silicic magma occurred almost exclusively after mixing.

9.8.4.9 Thermal and metasomatic effects

The shallow emplacement of large volumes of silicic ('granitic') magma into the crust brought about several changes in both the surrounding country-rocks and the intrusive rocks that formed (Ferry 1985b). Alteration processes were relatively short-lived, did not necessarily go to completion, and were caused by a combination of the large amount of heat liberated by the shallowly emplaced crystallising magmas and by the circulation of heated meteoric fluids, mainly supercritical H_2O.

As the various granites and finer-grained associated rocks crystallised, hydrous fluids were able to gain access, along crystal boundaries and, on a larger scale, along fractures that formed in response to volume reduction and stress release during cooling. Most of the fracture networks that formed were subsequently sealed by the precipitation of hydrothermal minerals, commonly in complex assemblages, to form quasi-planar veins.

Primary (magmatic) minerals, including amphibole, biotite, ferrohedenbergite/ferroaugite, fayalite, alkali feldspar, plagioclase, magnetite and ilmenite, locally underwent reaction with these fluids to form (common) secondary alkali feldspar, chlorite and montmorillonite. Less common was the formation of muscovite, calcite, epidote, prehnite, zeolites and pyrite. The alteration process led to minor changes in the bulk composition of the original rocks, with the addition of hydrogen, and a loss of Ca and Fe. Most of the mineralogical alteration occurred within the temperature range 350-450°C, mainly by solution-reprecipitation processes. However, mineral thermometry and barometry calculations suggest that certain minerals in the granites, clear alkali feldspar and plagioclase, Fe-Ti oxides, biotite, fayalite and, most likely, amphibole and ferrohedenbergite/ferroaugite, retain magmatic compositions, developed at temperatures in the range 650-750°C, and were unaffected by later, lower-temperature fluid-mineral reactions. These magmatic minerals have not isotopically equilibrated with hydrothermal fluids and have retained their magmatic stable isotopic (oxygen and hydrogen) signatures. However, the secondary minerals, listed above, have stable isotopic compositions that record fluid-mineral reactions that took place in the temperature range 350-450°C. Essentially, the granites retain two groups of minerals, those that are compositionally and texturally magmatic, and those that are compositionally and texturally of hydrothermal character.

Metamorphic and metasomatic effects caused by the intrusions are recorded in the Cambro-Ordovician (Chapter 2) and Jurassic strata (Chapter 3) of the district. The features within the Durness Group Cambro-Ordovician strata are more obvious and more widespread.

The whole of the Beinn an Dubhaich and parts of the Allt Feàrna–Creag Strollamus intrusions of the outer suite of granites (see above) are intruded into Cambro-Ordovician Durness Group dolostones. Both thermal metamorphic and metasomatic alteration of these carbonates have resulted, and these features are discussed in detail by Tilley (1947, 1948a, 1948b, 1948c, 1949, 1951), Hoersch (1977, 1979, 1981), Holness *et al.* (1989), Holness (1992) and Holness & Fallick (1994).

Apart from simple recrystallisation of dolomite within the dolostones, chert nodules within the dolostones have, to varying extents, been involved in metamorphic and metasomatic processes. Hoersch (1981) demonstrated that these nodules (70% quartz, 20% dolomite and 10% calcite) reacted with dolostone (99% dolomite and 1% calcite) to form reaction rims of calc-silicate minerals. In terms of incoming index minerals, which appear with increasing temperature as the contact with the granite is approached, Hoersch (1981) identified four distinctive zones: (1) talc-bearing (lowest temperature, 350–425°C); (2) tremolite-bearing (425–440°C); (3) diopside-bearing (440–520°C); and, (4) forsterite-bearing (highest temperature, 520–600°C) (Figure 9-175).

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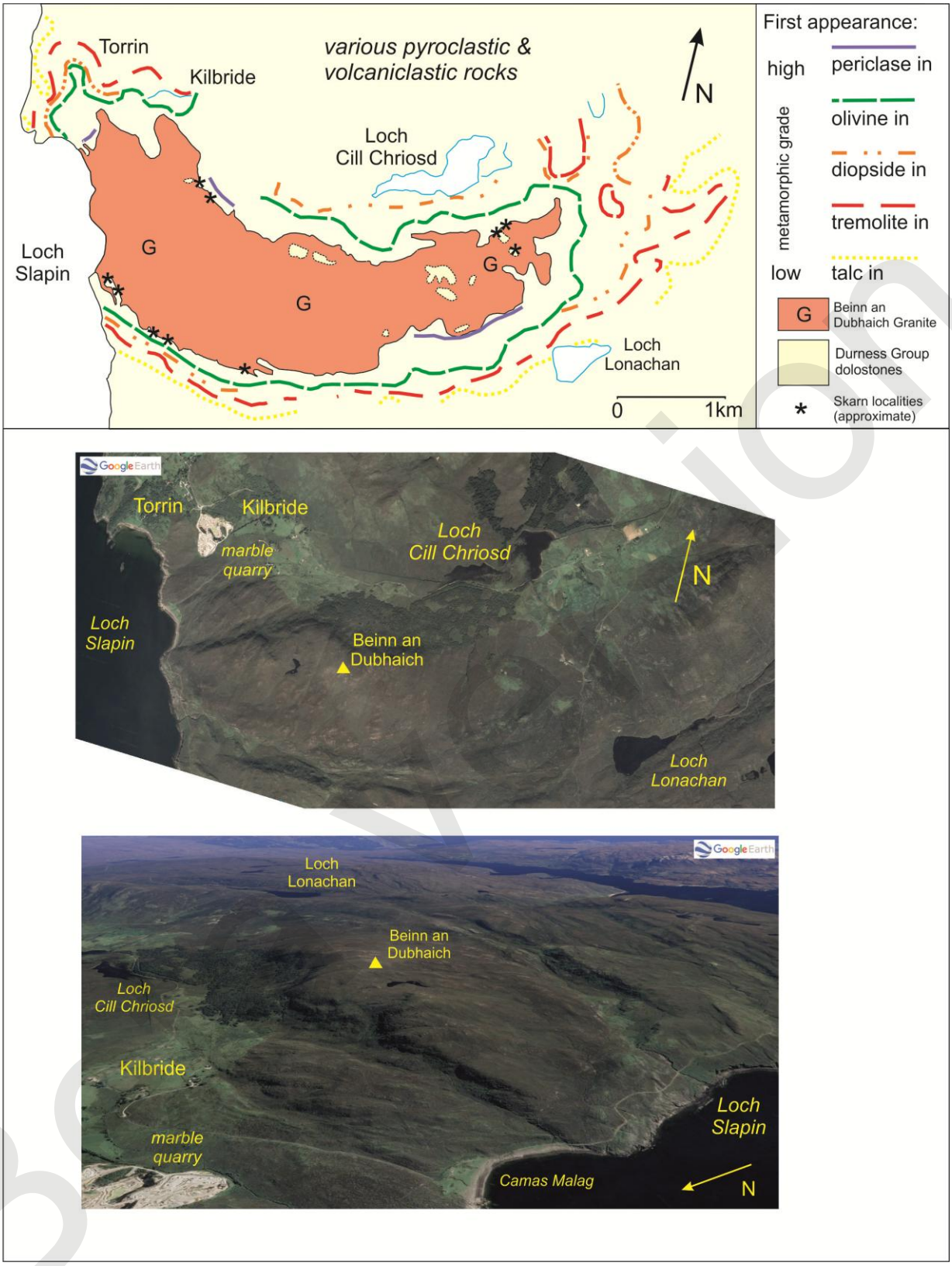


Figure 9-175: Contact metamorphic zones within the Cambro-Ordovician Durness Group dolostones on the east side of the Beinn an Dubhaich (granite) Intrusion (after Holness *et al.* 1989).

Holness (1992) re-examined the rocks within the metamorphic aureole and concluded that the metamorphism of dolostones within the sequence does not differ significantly from that of the chert nodule -bearing dolostones studied by Hoersch (1981) and, in addition, recognised the development of

periclase, formed by the breakdown of dolomite in the highest grade assemblage, but now completely pseudomorphed by brucite and minor magnetite.

The first sign of metamorphism in the dolostones is the growth of talc and calcite at chert-dolostone (nodule-matrix) boundaries. This metamorphic reaction continues until one of the reactants (generally the chert nodule) is totally consumed. Within the second zone, tremolite develops, occurring within nodules irrespective of whether silica had been, or had not been, totally used up. Within the third zone, the incoming of diopside is typically at the expense of any talc remaining within the nodule structure, together with some of the tremolite. Nearest the granite, small forsterite grains develop within diopside crystals.

Within *ca*. 100 m of the granite contact, the nodules take the form of alternating layers of forsterite (plus a small amount of calcite) and pure calcite (Figure 9-176). Tilley (1951) suggested that this may be due to a Liesgang phenomenon (secondary nested rings or bands caused by rhythmic precipitation within a fluid-saturated rock), although Hoersch (1981) points out that these bands may be the product of original zonation patterns present within the nodules.



Figure 9-176: Concentric alternating bands of forsterite (retrogressed to serpentine) and diopside within marbles from a large enclosure of country-rock, surrounded by granite, at the eastern end of the Beinn an Dubhaich Intrusion. Coin ca. 24 mm across.

Only the innermost isograd (separating the diopside and forsterite zones) can be traced with confidence in the field, running from the northern end of Loch Cill Chriosd (Kilchrist), east to the area south of Bheinn Shuardail, thence SW towards the area west of Loch Lonachan (Hoersch 1981; Holness *et al.* 1989). Due to the discontinuous nature of the exposure, the other isograds cannot readily be traced. Furthermore,

the sub-surface shape of the granite (see above) may mean that distances from the boundary, at the present level of erosion, do not actually represent true distances from the contact (for example, consider the possibility that the granite occurs at no great depth below Bheinn Shuardail).

During the metamorphism, the pressure was *ca*. 500 bars (equal to a depth of *ca*. 2 km) and the temperature of the silicic/granitic magma was *ca*. 750°C. Detailed mineralogical data and thermodynamic calculations indicate that the proportion of CO_2 present within the metamorphic fluid greatly influenced the reactions that took place (Hoersch 1981). For the duration of the metamorphism, externally derived aqueous fluid infiltrated the dolostones, most likely along pre-existing fracture systems, but with the highest grade (olivine-bearing) the rocks were pervasively infiltrated (Holness 1992).

Along the granite-dolostone contact, skarns developed locally, with widths typically less than 3 m (Tilley 1951) (Figure 9-177; Figure 9-178). They formed because of the movement of various components from the crystallising silicic magma and the heated country-rock dolostones, with deposition occurring within the contact zone. At the contact, the granite contains an alkali-rich pyroxene (in contrast to the normal mafic minerals, hornblende and biotite, see above). Tilley (1949) considered the pyroxene to be the product of a net removal of Al from the granitic magma into the dolostone country-rocks. To form the various skarn mineral assemblages, outlined below, Si, Al, Fe, B and F (within a fluid phase) were supplied by the crystallising granite (Tilley 1951).

In a detailed investigation of these skarns, Tilley (1951) describes over ten discrete outcrops from around the Beinn an Dubhaich Granite. In a traverse towards the granite, chert-bearing dolostones that have (simply) been metamorphosed (forsterite-bearing) typically give way to zones rich in forsterite and diopside (1–2 cm) and then pass into a hedenbergite-plagioclase-wollastonite rock of metasomatic origin.

Tilley (1951) recognises two main groups of skarns, characterised by their different mineral assemblages: Group 1, at the granite-country-rock contact and not containing any fluorine- or boron-bearing minerals; and, Group 2, on the country-rock side of Group 1 assemblages and containing fluorine- and boron-bearing minerals, together with magnetite and monticellite. Group 1 skarns can be independent of Group 2 skarns, but this is not common. Group 1 assemblages include: grossular garnet + wollastonite and hedenbergite + plagioclase (see above). The commonest Group 2 assemblage consists of magnetite + forsterite + chondrodite + clinohumite + diopside + grossular garnet + clinochlore. The boron- and fluorine-bearing minerals within the Group 2 skarns include: fluoborite, szaibelyite, datolite, ludwigite, and harkerite (boron-bearing); and, chondrodite, clinohumite, cuspidine and fluoborite (fluorine-bearing). The source of the boron and fluorine is considered to have been the crystallising granitic magma. The commonest (and most obvious) skarns involve magnetite, examples being the deposits south of the Old Manse at Kilchrist, and at Kilbride, south of Ashbank (Figure 9-177).

Studies of the granite-dolostone contact by ground magnetometry identified over 25 'anomalies', suggesting that several magnetite-bearing skarns may be present at no great depth below the present-day level of erosion (Whetton & Myers 1949).

Beta version



Figure 9-177: Magnetite-dominated skarn (black/brown) at granite-dolostone contact, SE of Ashbank, Kilbride, Strath. Pole *ca*. 1 m long.

In the Beinn an Dubhaich area, dolerite dykes intruded into the country-rock dolostones are cut by the younger granite (Figure 9-179). These dykes have been subjected to Ca-metasomatism during the alteration of the dolostones (see above). This metasomatism is readily noted within the dykes south of the old manse at Kilchrist, where primary pyroxene has been replaced by a secondary brown amphibole.

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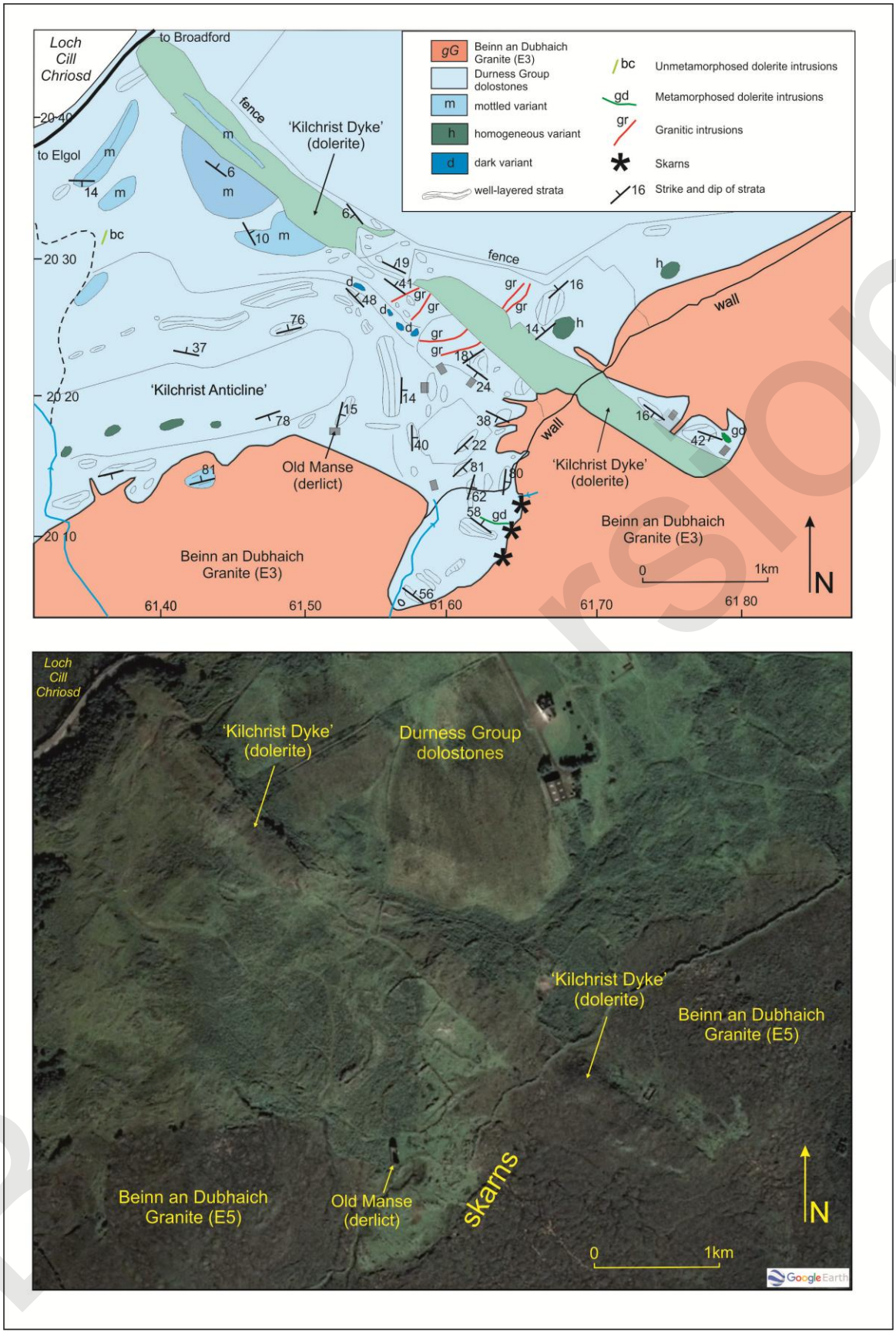


Figure 9-178: Schematic geological map illustrating the nature of the granite-marble contact at the Old Manse at Kilchrist, at the eastern end of the Beinn an Dubhaich Intrusion, and a Google Earth© image of the same area.

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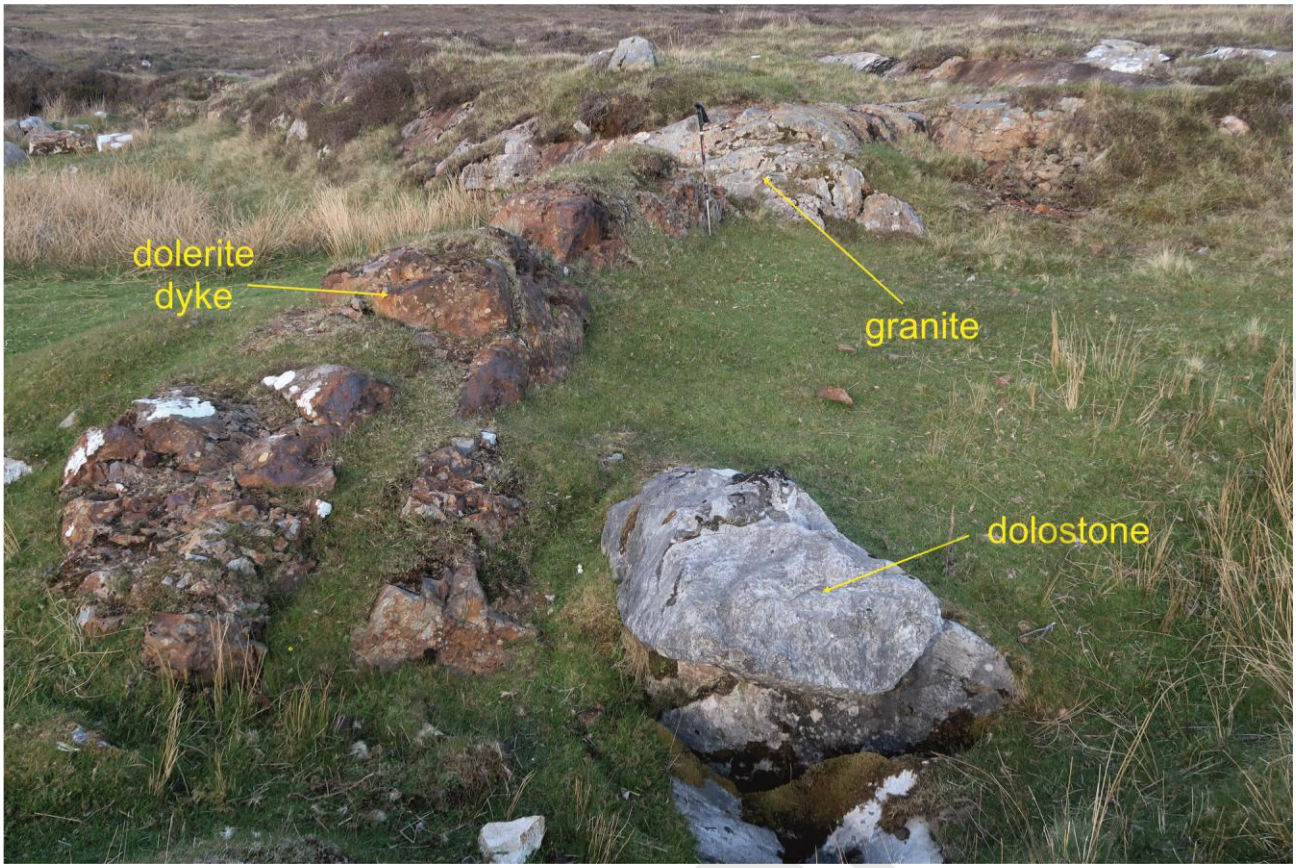


Figure 9-179: Altered Paleocene dolerite dyke within Cambro-Ordovician Durness Group dolostones close to the margin of the Beinn an Dubhaich Granite. Intrusion of the granite post-dates dyke emplacement. Pole *ca.* 1 m long at margin of granite. View towards the SE.

Mineral assemblages of metasomatic origin are also found within the marginal facies of the granite. In addition to the alkali-rich pyroxenes, described above, Tilley (1951) records pods and veins of clinopyroxene (diopside to hedenbergite), plagioclase (oligoclase to andesine), fluorite, grossular and andradite garnet, idocrase, epidote and allanite from within the granite south of the Old Manse at Kilchrist.

The only other metamorphic or metasomatic effects attributable to the granites of the ERHIC are found within the Middle Jurassic Bearreraig Sandstone Formation (Chapter 3) south of Dunan, between Glas-Bheinn Bheag and the Allt Strollamus. The boundary between the granite and the country-rock strata was originally described by Day (1931), who concluded that metasomatic processes were involved during the formation of the associated hornfelses, and that the contact is intrusive. Black (1955), however, determined that it is a fault. Furthermore, Black suggests that the contact-rocks are not true hornfelses that developed in response to high heat flow from the granite but are cataclastic in origin (essentially a fault breccia), with net additions of Fe, Mg, Ti and H_2O considered to have been deposited from volatiles streaming along the granite - country-rock boundary.

Smith (1960) re-investigated these contact rocks and defined six zones of increasing metamorphic grade, ranging from strata with very slight amounts of recrystallisation, through to hornfelses nearest to the granite, containing feldspar porphyroblasts (Figure 9-180). Smith (1960) concluded that during the development of these rocks there was a net removal of K, Na, Mg, Fe and H_2O from the granite, as it crystallised, into the country-rocks.

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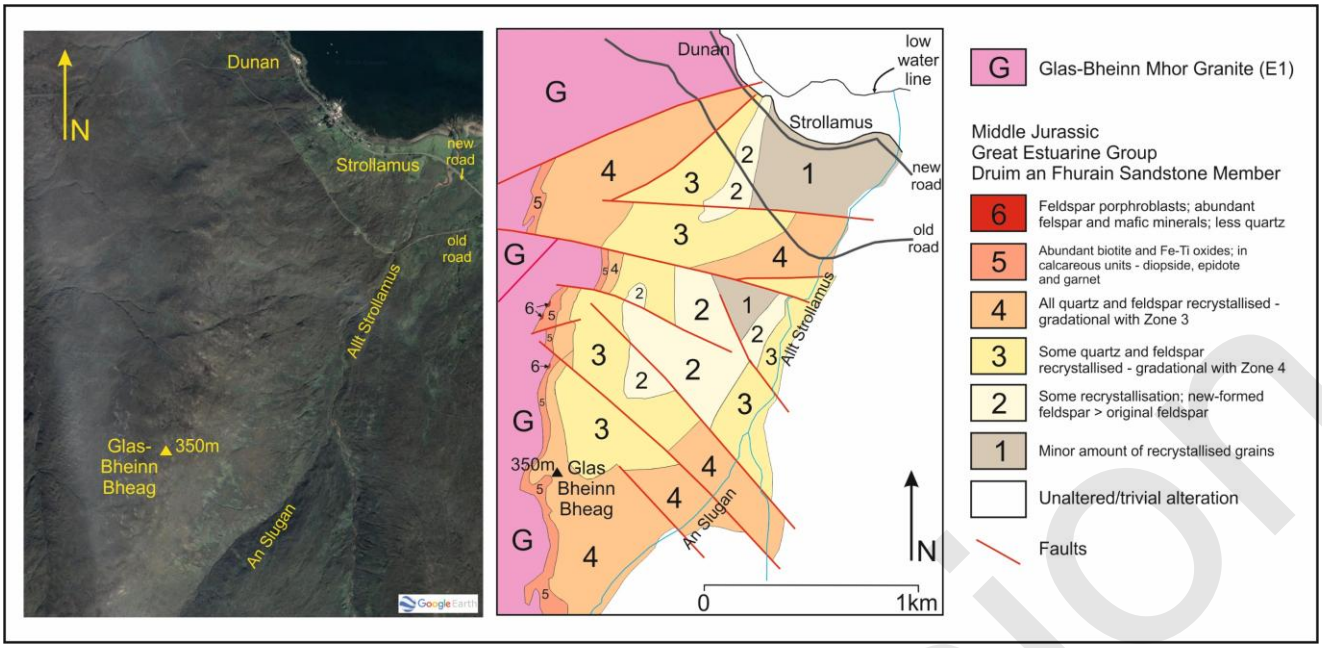


Figure 9-180: Geological sketch map illustrating the nature and distribution of the contact metamorphic zones within Middle Jurassic Bearreraig Sandstone Formation strata east of Glas-Bheinn Bheag, adjacent to the ERHIC Beinn na Cró Granite, and a Google Earth© image of the same area. (after Smith 1960).

9.9 Rum Central Complex

9.9.1 Introduction

The Rum Central Complex (Figure 9-1; Figure 9-181) was emplaced into sandstones of the Late Proterozoic Torridon Group (Chapter 2) which, together with the Lewisian Gneiss Complex (Chapter 2), form the ridge (or horst) that separates the Sea of the Hebrides and the Inner Hebrides Mesozoic sedimentary basins (Chapter 3) (Fyfe *et al.* 1993; Binns *et al.* 1974). There were at least three distinct phases in the growth and decay of the Rum Central Complex (Emeleus 1997). Phase 1 was dominated by caldera-related, silicic magmatism and the development of an arcuate system of faults, termed the Main Ring Fault. Basic and ultrabasic magmas were intruded mainly during Phase 2, when numerous minor intrusions, and gabbros and layered ultrabasic rocks were emplaced. Phase 3 was marked by deep subaerial erosion and unroofing of the central complex, with intermittent burial of the developing topography by basaltic lavas of the Skye Lava Field (dealt with in detail in Chapter 6), and by the coarse detritus eroded from the central complex and its surroundings.

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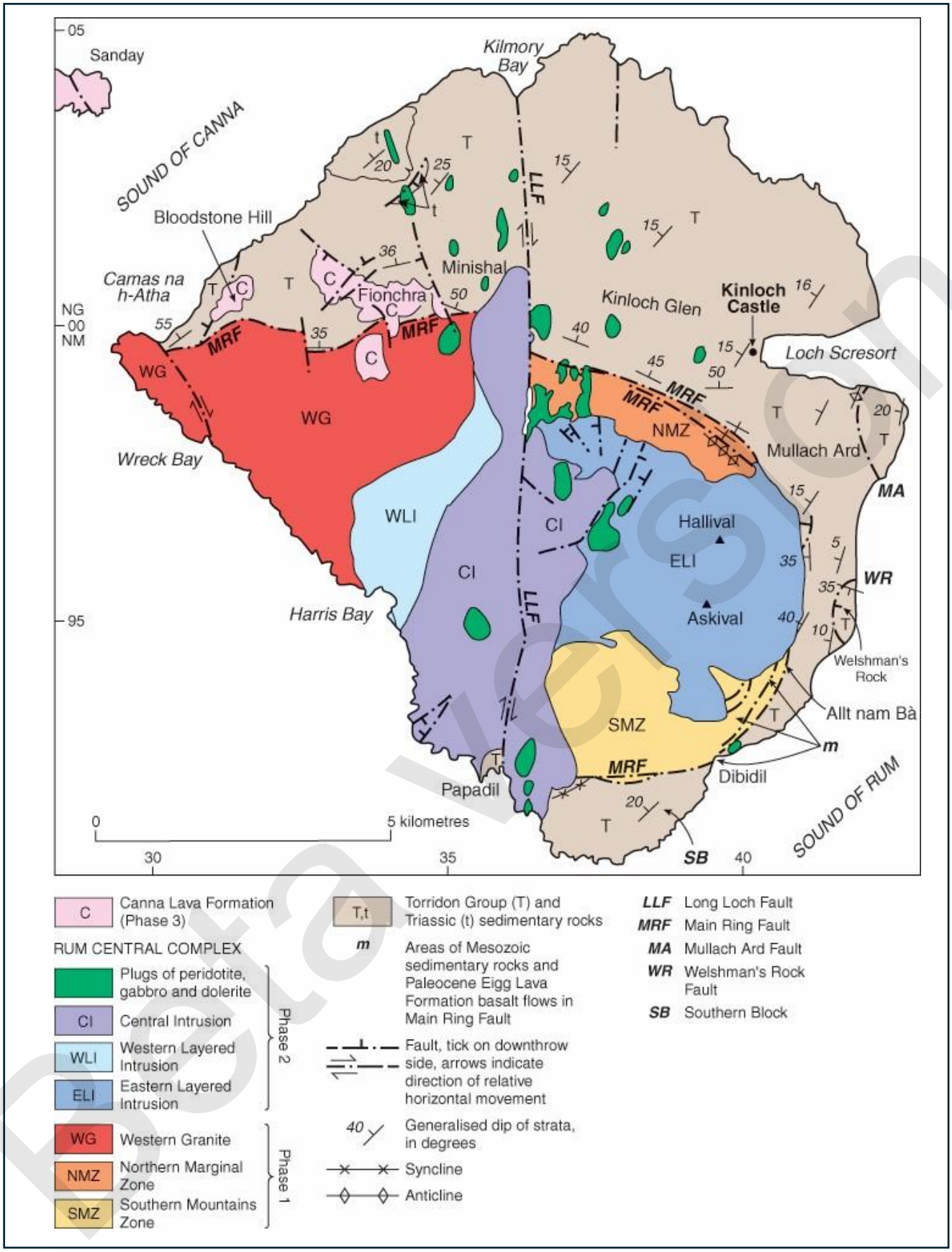


Figure 9-181: Principal divisions of the Rum Central Complex (after Emeleus & Bell 2005).

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Emeleus (1997) and Emeleus & Troll (2014) provide an account of the Rum Central Complex, the latter an update of Emeleus & Bell (2005), and both form the basis of the summary set out below.

Pre-Paleocene

Granitic gneiss of the Lewisian Gneiss Complex (Amphibolite Facies), overlain by >2.5 km of Late Proterozoic Torridon Group sandstones and siltstones, a thin covering of Lower Jurassic Broadford Beds Formation strata (limestone, sandstone and siltstone) and Paleocene basaltic lavas of the Eigg Lava Formation [All intruded by dykes of the Muck Swarm and the Rum Sub-swarm prior to Stage 1; the Long Loch Fault was most likely active well before the Paleocene].

Paleocene Rum Central Complex: Stage 1

Initiation of the Main Ring Fault (MRF) accompanied by major central uplift, with subsequent subsidence leading to caldera formation, the collapse of caldera walls and the formation of debris avalanche deposits, with concomitant intrusion and effusion of silicic and mixed silicic/basic magmas and emplacement of the Am Màm intrusive breccias. Severe distortion of country-rocks adjoining the MRF and collapse of major masses of country-rocks off the rising dome, as at Welshman's Rock. Emplacement of the Western Granite. Possible further central uplift on the MRF.

Paleocene Rum Central Complex: Stage 2

Change to basic and ultrabasic magmatism, indicated by the intrusion of basaltic cone-sheets and further intrusion of dykes of the Rum Sub-swarm, followed by emplacement of ultrabasic rocks (peridotites and troctolites) and gabbros of the Central Intrusion, with construction of the Layered Suite (the Eastern and Western layered intrusions) through successive sheet-like injections of ultrabasic and basic magmas from the Central Intrusion, ultimately supplied by feeders on the Long Loch Fault. Intrusion of numerous gabbro and peridotite plugs pre- and post-dating the MRF. Further central uplift most likely accompanied emplacement of the Stage 2 intrusions as the Central Complex developed beneath a cover of earlier uplifted rocks (Stage 1 and pre-Palaeocene) and (contemporaneous?) lavas.

Post Central Complex

Immediately following the formation of the Central Complex, a succession of deep valleys developed during vigorous erosion of the Rum Volcano, becoming rapidly filled with coarse clastic debris (conglomerates, breccias) derived from the Central Complex and surroundings; these are interbedded with predominantly basaltic lavas belonging to the Canna Lava Formation (Palaeocene Skye Lava Group) which banked up against the flanks of the volcano. Some north- to NW-trending basalt dykes post-date the Canna Lava Formation, although regional dykes were most likely intruded throughout the Paleocene and a subsequent heating event (at *ca*. 45 Ma) indicates that activity may have been prolonged. Significant right-lateral movement on the Long Loch Fault post-dates the Central Complex. [Rum underwent further deep erosion by local glaciers and by ice from the Scottish Mainland during the Pleistocene].

9.9.2 Age and geophysical characteristics

Hamilton *et al*. (1998) applied U–Pb and $^{40}Ar/^{39}Ar$ dating techniques to establish that the Rum Central Complex was emplaced at *ca*. 60.5 Ma (Chapter 5). This magmatic activity spanned *ca*. 500,000 years, encompassing the Phase 1 caldera formation, explosive rhyolitic eruptions, and the Phase 2 intrusion of the layered basic-ultrabasic rocks. Subsequently, Troll *et al*. (2008) provided confirmation on the timing of the initiation of volcanic activity within the Rum Central Complex utilising single-crystal $^{40}Ar/^{39}Ar$ laser

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dating of twenty plagioclase phenocrysts from rhyodacite ash-flow sheets and determined a mean apparent age of 60.83 ± 0.27 Ma, with a dominant peak at 60.33 ± 0.21 Ma. The presence of minor age shoulders at approximately 61.4 Ma and 63 Ma is attributed to the incorporation of recycled feldspar crystals.

McQuillin & Tuson (1963) conducted a gravity measurement study over Rum, Eigg and Canna to constrain subsurface structure. Observed gravity anomalies indicate a pronounced positive Bouguer effect, reflecting a substantial density contrast between the basic–ultrabasic plutonic rocks and surrounding sedimentary strata. Data suggest the intrusive body extends to a considerable depth, with a roughly cylindrical or conical geometry, consistent with emplacement from a deep-seated magma source (Figure 9-182).

The intrusive and extrusive rocks are reversely magnetised, and it is likely that emplacement of the central complex occurred over about 1 million years, during magnetic anomaly C26R (Figure 9-183).

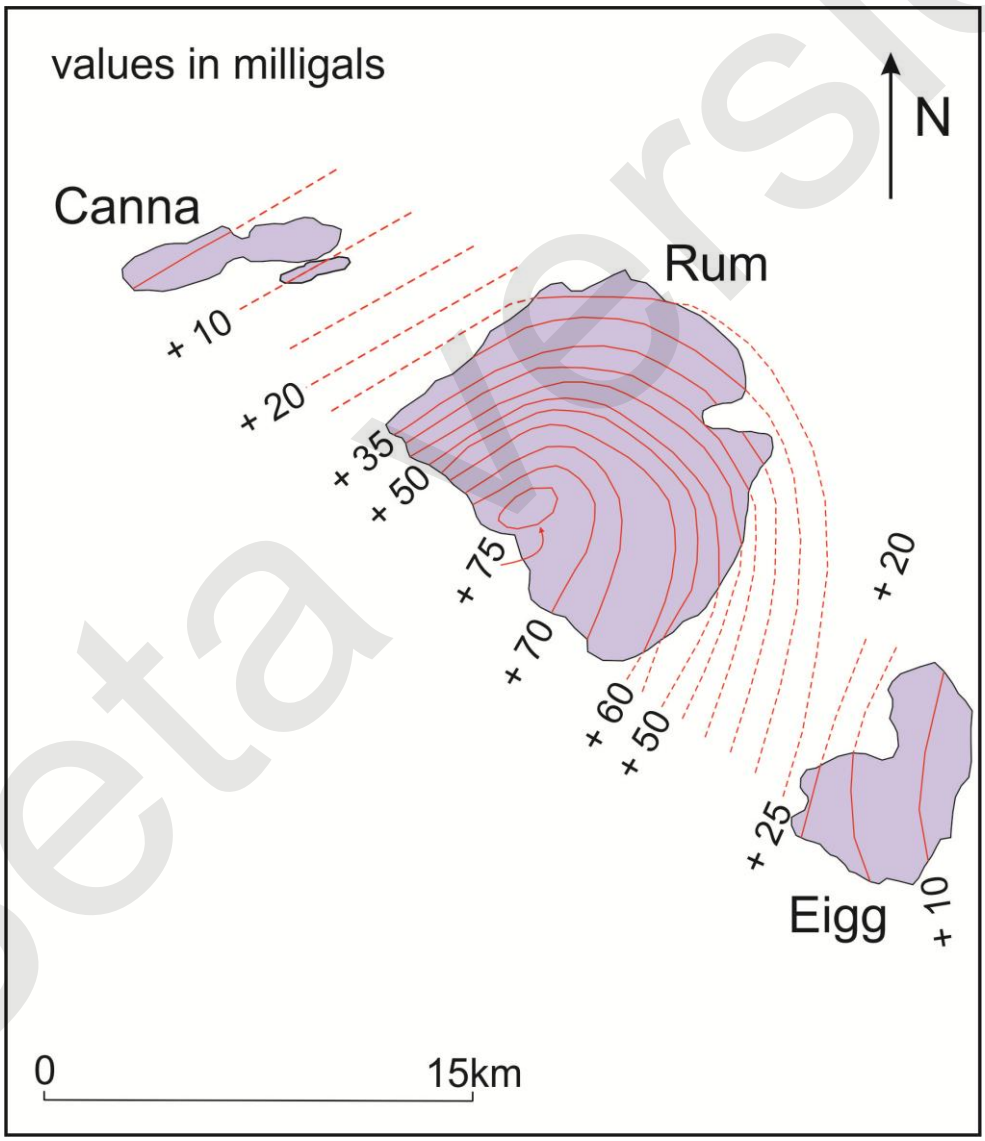


Figure 9-182: Bouguer anomaly map for the islands of Rum, Eigg and Canna. Contour interval, 5 milligals (after McQuillin & Tuson 1963).

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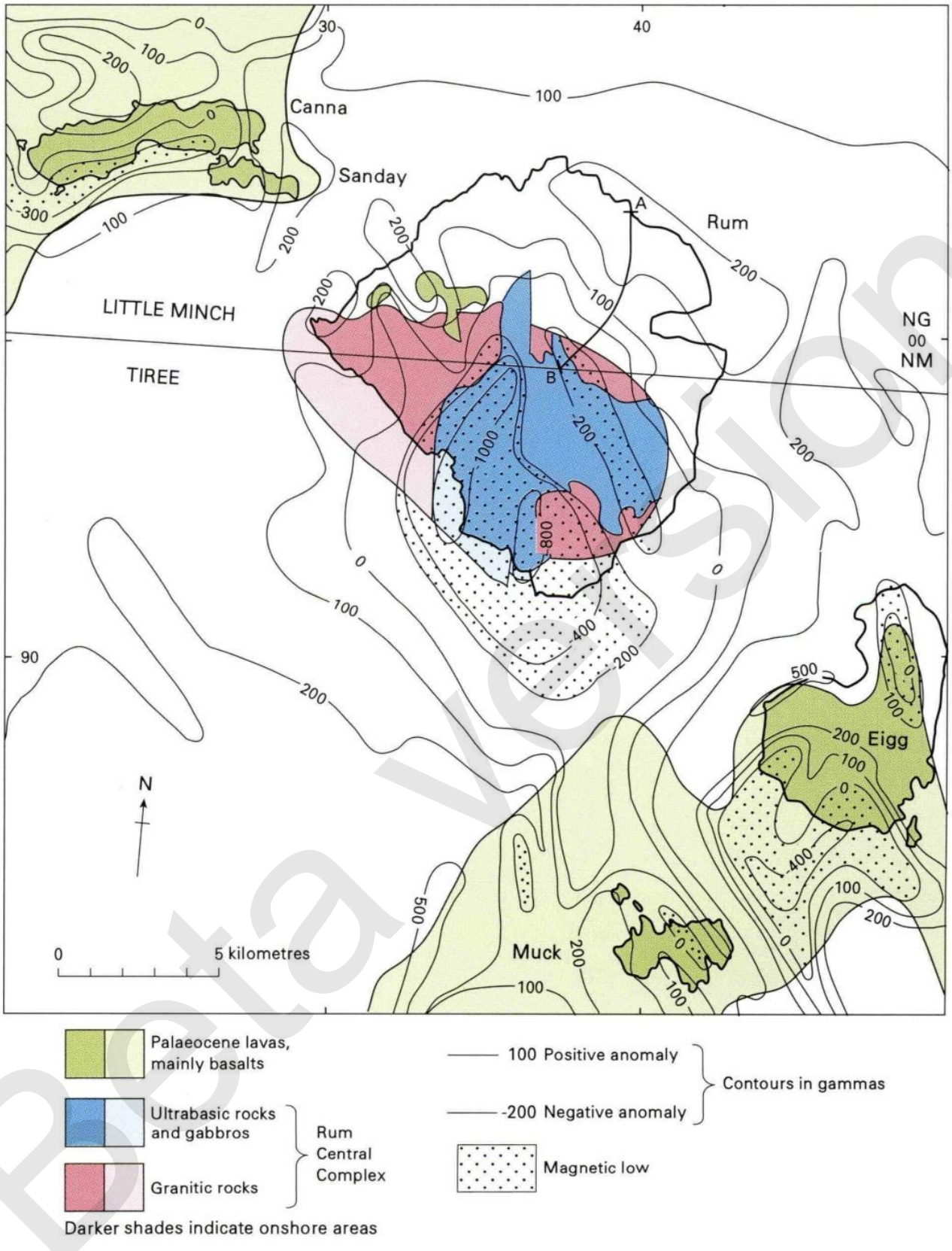


Figure 9-183: **Simplified aeromagnetic map of the Small Isles. Based on the 1:250 000 aeromagnetic anomaly maps Tiree and Little Minch. The line A–B refers to the traverse along which Robinson and McClelland (1987) measured the palaeomagnetisation of Torridon Group rocks on Rum (after Emeleus 1997).**

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9.9.3 Phase 1 of the Rum Central Complex: caldera development and fill in the Northern Marginal Zone (NMZ)

9.9.3.1 Stratigraphy of the Northern Marginal Zone (NMZ)

The rock units within the Northern Marginal Zone (NMZ) were formed during Phase 1 (Dunham 1968; Emeleus 1997) (Figure 9-184; Figure 9-185; Figure 9-186). Initial activity involved uplift within the Main Ring Fault, causing slivers of the Lewisian Gneiss Complex and basal members of the Torridon Group (Chapter 2) to be elevated by as much as 2 km inside the fault system. The uplift was accompanied by tilting, deformation and doming of the Torridon Group rocks that surrounded and overlay the central complex. At this time, the two major masses of Torridonian sandstone that form Mullach Ard and Welshman's Rock, each now underlain by low-angle faults inclined at about 35° to the east and NNE, respectively, are thought to have slid off the developing dome. The Torridonian rocks south of the Main Ring Fault in southern Rum most likely comprise a similarly displaced block.

The volcanic sequence in the NMZ is described in detail by Troll *et al.* (2000, 2004) (Figure 9-185; Figure 9-186). Magmatic tumescence and incremental chamber inflation induced the initial doming, followed by collapse without eruptive activity, forming a roughly circular 'proto-caldera'. This collapse produced megablocks, blocks, and boulders of Torridonian sandstone, generating heterolithic collapse breccias up to 170 m thick that infilled an uneven caldera floor - evidence for piecemeal subsidence (Figure 9-187; Figure 9-188). The breccias are both matrix- or clast-supported and interpreted as debris avalanche deposits (Troll *et al.* 2000, 2004).

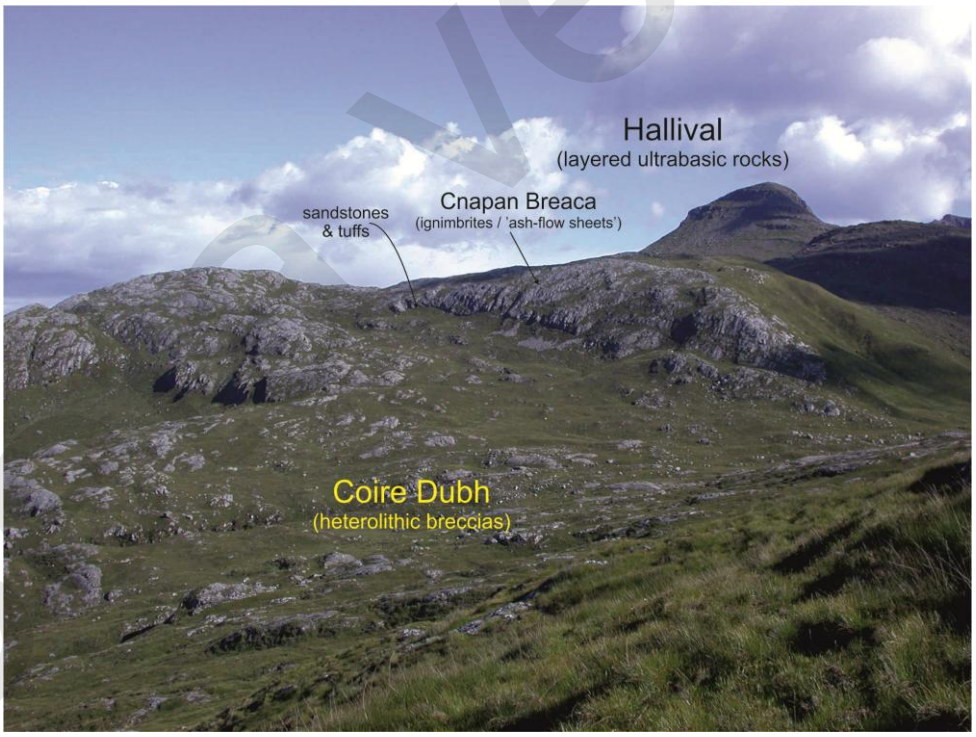
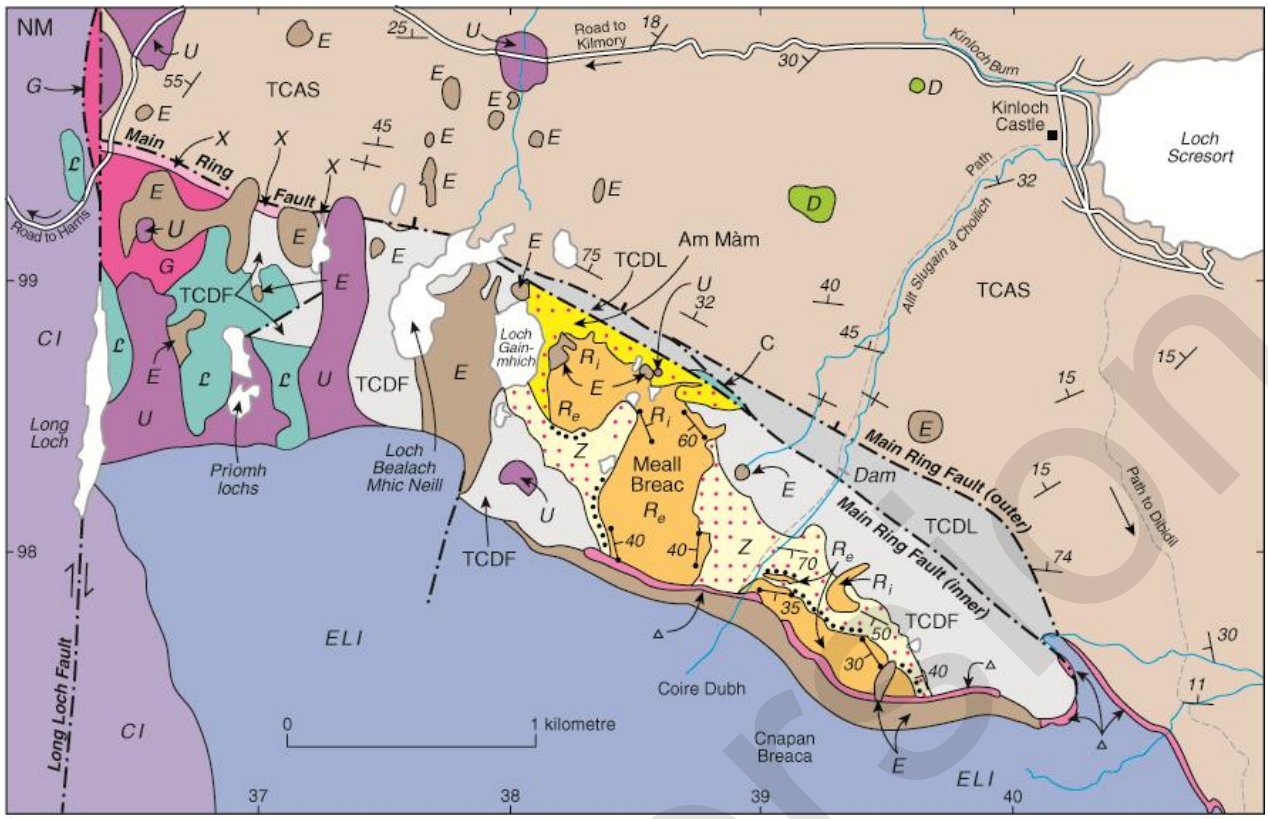


Figure 9-184: Panoramic view of the Northern Marginal Zone (NMZ) in the Coire Dubh area viewed from Meal Breac (towards the SE). Rocks of the NMZ form the low foreground (Coire Dubh Breccia) and the pale crags and outcrops on Cnapan Breaca (centre) are rhyodacite ignimbrites. The base of the Cnapan Breaca crags marks the position of fine-grained sandstones and bedded tuffs. The easily weathered marginal gabbro forms the grassy area on the right-hand flank of Cnapan Breaca. The terraced slopes leading up to Hallival mark the positions of troctolite ('allivalite') in layered units in the ELI. [Photograph courtesy of Valentin Troll]

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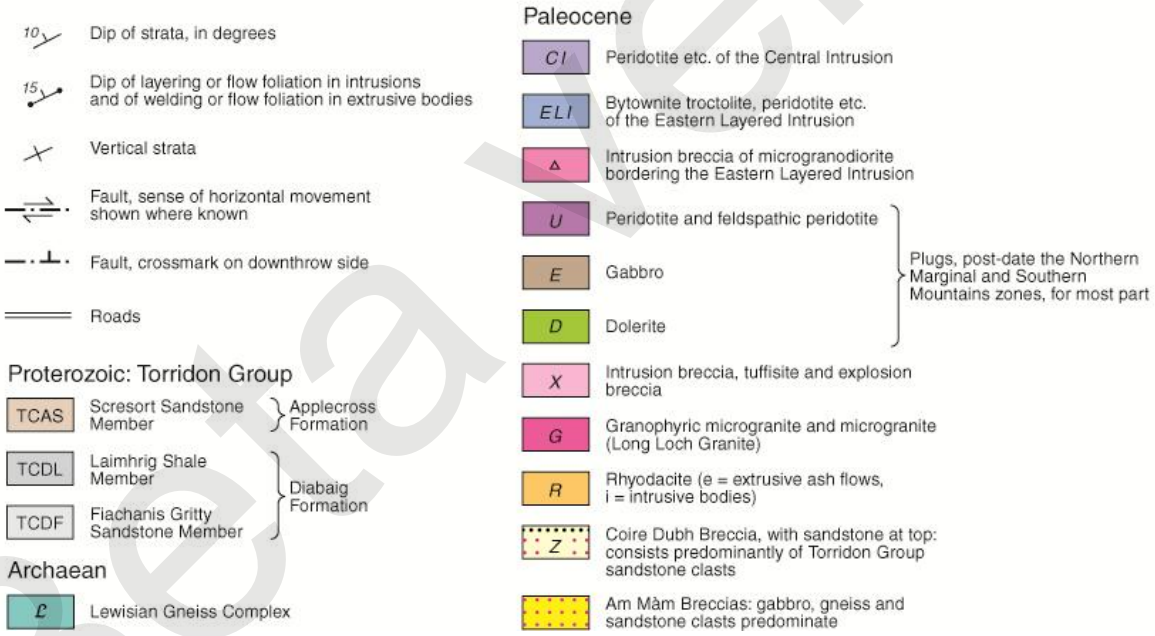


Figure 9-185: Geological Map of the Northern Marginal Zone (NMZ) (after Emeleus 1997).

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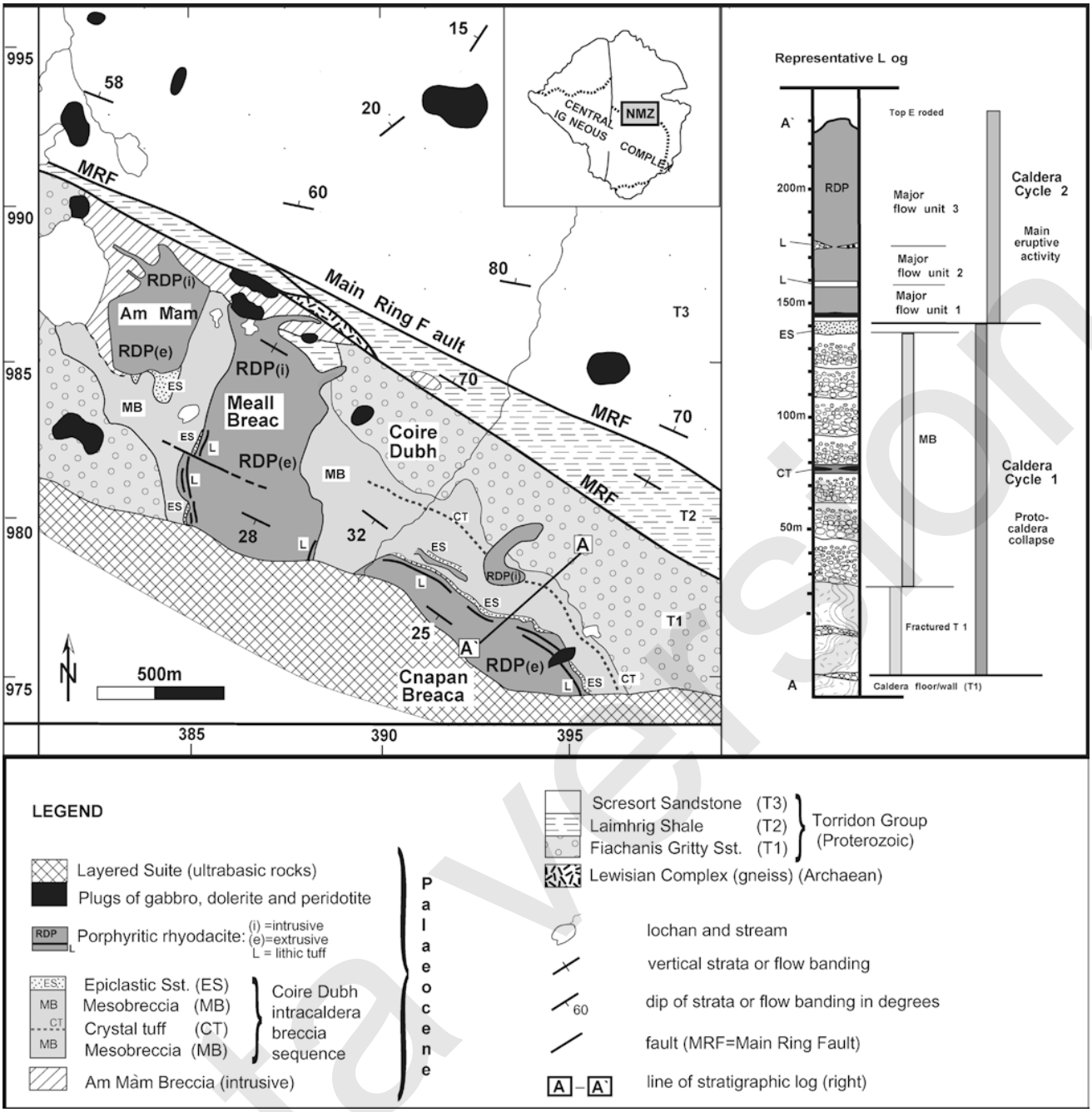


Figure 9-186: Simplified geological map of the Northern Marginal Zone and stratigraphic log section through the intra-caldera succession. [Figure courtesy of Valentin Troll]

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Figure 9-187: Coire Dubh Breccia with a chaotic assemblage of matrix-supported, angular and sub-angular clasts mainly derived from the Torridonian Fiachanis Gritty Sandstone Member. Compass *ca.*10 cm long.



Figure 9-188: Coire Dubh Breccia with a chaotic assemblage of matrix-supported, angular and sub-angular clasts mainly derived from the Torridonian Fiachanis Gritty Sandstone Member. Compass *ca.*10 cm long.

Overlying the breccias is a 3-6 m thick sequence comprising epiclastic sandstones deposited from washout of fine material derived from the breccias and crystal tuffs rich in plagioclase identical to the

phenocrysts in the overlying rhyodacite ignimbrites ('ash-flow sheets'; Troll *et al.* 2000, 2004). Similar material is interbedded with the breccias, albeit in thin, laterally discontinuous beds.

Renewed resurgent doming produced a fracture network. The clastic rocks are overlain by thick (≤ 100 m) rhyodacite ignimbrites, sourced from a feeder system proximal to the caldera ring-fault, and locally grade into intrusive rhyodacite. Eutaxitic textures, characteristic of ignimbrites, are common (Figure 9-189; Figure 9-190; Figure 9-191). Eruption of the quartz-feldspar -phyric rhyodacite magma may have been caused by the mingling of silicic and basaltic magmas within the subjacent magma chamber, indicated by fragments of basaltic material dispersed throughout the ignimbrites. The rhyodacite intrusions, essentially ignimbrites with a eutaxitic texture, grade laterally into the extrusive (ignimbrite) facies, indicating a continuum from the subsurface conduit to surface deposition.

Overall, the stratigraphic architecture delineates a caldera-fill succession: basal collapse breccias and sandstones, overlain by thick, compositionally mixed rhyodacite ignimbrite(s), with intricate feeder-deposit relationships revealing the spatial-temporal evolution of magma mixing processes.

The most extensive outcrop of ignimbrite is on Meall Breac, where it reaches at least 100 m in thickness. This body is truncated to the south by gabbro, with the contact marked by intrusion breccias (the Am Màm Breccias, see below) and various hybrid rocks (Figure 9-185) (Dunham 1964). Although the upper contact of the ignimbrite is not visible, at both the SW and SE margins, it overlies and is interlayered with fragmental deposits that dip at low angles.

At the SW end of Meall Breac is *ca.* 2 m of pale, unbedded feldspathic sandstone overlain by *ca.* 2 m of coarse breccia with well-bedded sandstone clasts, above which is a stratified tuff, overlain by the rhyodacitic ignimbrite. A thin breccia layer (10–30 cm thick), located a few metres above the ignimbrite base, contains sandstone and siltstone clasts within a comminuted sandy matrix. This layer shows a sharply defined upper contact but an irregular, gradational lower surface. It maintains a consistent position within the rhyodacite for *ca.* 200 m north of the gabbro, before breaking into an S-shaped, south-facing overfold. These features suggest disruption during rheomorphic flow of the ignimbrite. Similar breccias occur SE of Meall Breac.

At the northern summit of Meall Breac, rhyodacite is in a steep to vertical contact with breccia. A nearby dyke-like intrusion cuts sandstone *ca.* 100 m to the ESE, while a broad rhyodacite dyke intrudes both sandstone and the Am Màm Breccia (see below) to the north. Near the summit, vertical banding - interpreted as a primary pyroclastic fabric - is common. This contrasts with low-angle, discontinuous banding seen at the southern end.

The Am Màm rhyodacite outcrop has a similar structure. To the south, it overlies pale sandstone above breccia; to the north, it intrudes both the Am Màm Breccia (see below) and gabbro.

The Cnapan Breaca rhyodacite forms a south-dipping sheet (35°), at least 80 m thick. Its base sharply overlies fragmental rocks (Figure 9-186). To the west of Cnapan Breaca, a separate rhyodacite unit underlies the main sheet and is cut by a microgranite sheet. It may represent an earlier ignimbrite that filled a shallow depression. A crescent-shaped rhyodacite body, *ca.* 400 m south of the Coire Dubh hydro-electric dam, contains abundant inclusions - angular sandstone and rounded basic igneous fragments - suggesting turbulent mingling at a shallow crustal level.

Beta Version



Figure 9-189: The northern flank of Meall Breac, composed of rhyodacite ignimbrites. In the distance (left) is Fionchra, comprising an outlier of Paleocene volcanic rocks, an outlier of the Skye Lava Field.



Figure 9-190: Attenuated fiammé in porphyritic rhyodacite ignimbrite, SW end of Meall Breac, NMZ. The foliation defined by the fiammé points towards the centre of the caldera, possibly implying flow from the caldera margin towards its interior. [Photograph courtesy of Valentin Troll]

Boundary version



Figure 9-191: Attenuated fiammé in porphyritic rhyodacite ignimbrite, SW end of Meall Breac, NMZ. The foliation defined by the fiamme points towards the centre of the caldera, possibly implying flow from the caldera margin towards its interior. Compass *ca.*10cm long. [Photograph courtesy of David Brown]

9.9.3.2 Interpretation of the NMZ rhyodacites

As an aside, how the geological interpretation of the rhyodacites has evolved considerably over time is worthy of comment. Judd (1874) originally proposed that the rhyodacites were lavas. Later, Geikie (1897) observed features suggesting an intrusive origin. Harker (1908) provided the first comprehensive study of the rhyodacites, detailing their field relationships, petrography, and chemistry. He concluded that the rhyodacites post-date the gabbros which margin the ultrabasic layered rocks, based on the presence of rhyodacite veins cutting and brecciating the gabbros.

In contrast, Bailey (1945) argued that field relationships indicated the opposite: the gabbros truncate the rhyodacites. Hughes (1960a) and Dunham (1964) reconciled these conflicting interpretations by demonstrating that the veins and breccias resulted from ultrametamorphism of the rhyodacites by the later-emplaced gabbros. They also established a close association between the rhyodacites, coarse breccias, and intrusive tuffaceous rocks or ‘tuffisites’ (Hughes 1955, 1960a; Dunham 1968). Dunham (1964) conducted a detailed study of intrusion breccias and hybrid rocks formed at the rhyodacite–gabbro contact (see below).

Williams (1985) noted that the rhyodacite on Cnapan Breaca exhibits features typical of pyroclastic deposits, such as welded tuffs, and likened the sheet to an ignimbrite. This view was supported by

personal observations from M. Errington (1989) in the Southern Mountains Zone (see below). Bell & Emeleus (1988) further suggested that the rhyodacitic welded tuffs and breccias may represent caldera-fill deposits. However, some rhyodacite bodies - both in the Northern Marginal Zone and the Southern Mountains Zone - are clearly intrusive but still retain pyroclastic characteristics (cf. Bell & Emeleus 1988). In this respect, interpretations have come full circle, returning, in part, to Judd's original proposal.

9.9.3.3 Tuffisite dykes

Tuffisite dykes on Rum represent volatile-driven injections of fragmented magma and wall rock into fractures within the roof of the Paleocene chamber complex (Figure 9-192; Figure 9-193; Figure 9-194). They occur as narrow, fine-grained, poorly sorted, and locally welded veins and dykes cutting both pre-Paleocene country-rocks, as well as Paleocene volcanic units, and consist of ash, glass shards, crystal fragments, and lithic debris. Their textures and cross-cutting relationships indicate formation by explosive gas overpressure and fragmentation, with volatile/ash suspensions forced into fractures during the silicic (rhyodacite) eruptions. These bodies are not simple magmatic dykes but record pneumatic injection and fracture-filling, analogous to tuffisite veins observed in modern conduit systems beneath lava domes. Their presence demonstrates that explosive rhyodacitic volcanism on Rum was accompanied by pervasive fracturing and degassing of the chamber roof, and that volatile escape pathways were fundamental to caldera evolution.



Figure 9-192: Tuffisite dyke, essentially an intrusive tuff, Coire Dubh. Compass *ca.* 10 cm long. [Photograph courtesy of David Brown]

Beta version



Figure 9-193: Detail of tuffisite dyke, essentially an intrusive tuff, Coire Dubh. Compass *ca*. 10 cm long. [Photograph courtesy of David Brown]



Figure 9-194: Tuffisite dyke, essentially an intrusive tuff, Coire Dubh. Penknife *ca*. 10 cm long. [Photograph courtesy of David Brown]

9.9.3.4 The Am Màm Breccias

Nicoll *et al.* (2009) reassessed the Am Màm intrusion breccia, emplaced in the NMZ and re-established it as a syn-caldera unit rather than a pre-caldera precursor. The breccia forms a distinctive intrusive body adjacent to the Main Ring Fault, preserving a crucial record of early basic magma input and crustal melting during the initiation of the central complex.

The breccia consists of a rhyodacitic matrix with abundant basic micro-enclaves and clasts ranging from centimetre-scale fragments to megablocks exceeding 200 m (Figure 9-195; Figure 9-196; Figure 9-197). Clast lithologies include Lewisian gneiss, Torridonian sandstone, and coarse gabbro, documenting deep sampling of the crust and shallow igneous intrusions during emplacement. The rhyodacitic matrix contains lobate basaltic enclaves displaying chilled margins, indicating physical mingling of hot basic magma with a cooler silicic host. Texturally, feldspar phenocrysts show resorption embayments, sieve textures, and zoned rims, consistent with disequilibrium growth under fluctuating thermal and compositional conditions.



Figure 9-195: Am Màm Breccias on the west side of Am Màm, viewed towards the NW across Loch Gainmhich and Loch Bealach Mhic Nèill to Orval and Fionchra. [Photograph courtesy of David Brown]

Be version



Figure 9-196: Am Màm intrusion breccia, with rounded blocks of gabbro in a rhyodacitic matrix, intruded by a thin basaltic dyke. Hammer *ca*. 40 cm long. [Photograph courtesy of David Brown]



Figure 9-197: Detail of Am Màm breccia on Am Màm, illustrating interaction/mingling between basaltic and silicic magmas. Compass *ca*. 10 cm long. [Photograph courtesy of David Brown]

Contact metamorphism is evidenced by hornfelsed sedimentary blocks and recrystallised gneiss fragments, testifying to high-temperature heating from early basic intrusions prior to and during breccia

emplacement (Emeleus 1997). Geochemical and isotopic analyses demonstrate that the silicic matrix was derived from partial melting of Lewisian Amphibolite-Facies gneiss, incorporating up to *ca*. 60 % crustal material. The gabbroic blocks similarly show evidence of crustal assimilation (≤ 20 %), suggesting that both enclave and matrix compositions reflect magma–crust interaction.

The emplacement mechanism was structurally controlled: propagation of basic-silicic magmas into zones of weakness along the ring fault system facilitated stoping and brecciation of country-rock, accompanied by mingling and limited hybridisation of contrasting magmas. The juxtaposition of crustal xenoliths, basaltic enclaves, and rhyodacitic host records a dynamic syn-caldera environment, where intrusion, anatexis, and explosive brecciation occurred in rapid succession.

The Am Màm breccia captures the initiation of crustal melting beneath Rum, triggered by underplating basic magmas. This process highlights the potential of mantle-derived melts to generate substantial silicic products through crustal anatexis, even at an early stage of central complex growth. The textures and enclave–host relationships provide direct evidence that magma replenishment, mingling, and assimilation operated as key mechanisms in destabilising the reservoir, setting the stage for subsequent silicic ignimbrite eruptions and the Phase 2 layered ultrabasic and basic intrusions (see below).

In conclusion, Nicoll *et al*. (2009) established that the Am Màm breccias are syn-caldera basic intrusions, involving crustal anatexis and magma hybridisation, emphasising their role in the transition from early silicic to sustained basic magmatism in the Rum Central Complex. Their study demonstrates how magma–crust interaction at shallow levels shaped the evolution of the Hebridean Igneous Province.

9.9.4 Phase 1 of the Rum Central Complex: caldera development and fill in the Southern Mountain Zone (SMZ)

9.9.4.1 Stratigraphy of the Southern Mountain Zone (SMZ)

The Southern Mountains Zone (SMZ) of the Rum Central Complex provides an unusually well-preserved record of the interplay between tectonic, sedimentary, and volcanic processes at the roof of a shallow Paleocene magma chamber (Figure 9-198; Figure 9-199; Figure 9-200; Figure 9-201; Figure 9-202; Figure 9-203; Figure 9-204). Holohan *et al*. (2009) reinterpreted this area, long interpreted in terms of cryptic subsurface explosions and intrusive rhyodacite sheets (Hughes 1960), and demonstrated instead that its succession represents mass-flow breccias and ignimbrites emplaced in direct response to chamber-roof uplift and subsequent caldera subsidence.

The volcanic sequence of the SMZ exceeds 200 m in thickness and overlies uplifted Precambrian basement within the structural block interior to the Main Ring Fault. This basement shows evidence of both uplift and later subsidence, establishing from the outset that deformation of the chamber roof governed subsequent deposition. The lower part of the succession consists of Coire Dubh-type breccias (see above), previously regarded as intrusive explosion breccias but reinterpreted by Holohan *et al*. (2009) as debris- and stream-flow accumulations. These deposits comprise angular country-rock clasts, usually less than a metre in size, within a sandy to silty matrix, locally displaying bedding, grading, and intercalation with sandstones and lithic tuffs. Such features are incompatible with *in situ* explosive fragmentation but are consistent with slope failures and mass-wasting processes on an uplifted and over-steepened terrain. The repeated occurrence of these breccias therefore records recurring instability of the chamber roof during progressive uplift, punctuated by quieter intervals that allowed finer-grained sedimentation.

Beta version

Overlying and interfingering with the breccias are rhyodacite sheets, which have previously been interpreted as intrusions. These bodies are laterally extensive, tens of metres thick, and either concordant or gradational with their substrates. They contain basal lithic tuffs and abundant fiammé, produced by the flattening of pumice during welding, typical of ignimbrites. Welding varies from moderate to dense, consistent with deposition from hot pyroclastic density currents followed by compaction and consolidation. Crucially, a steep, fiammé-bearing rhyodacite body cutting through adjacent units is interpreted as an ignimbrite vent system, recording the pathways through which pyroclastic flows erupted. This recognition eliminates the intrusive model and confirms that the rhyodacite sheets are the products of explosive silicic eruptions.

Units previously described as megabreccias were also re-evaluated. Rather than chaotic collapse deposits, they are interpreted as coherent blocks of Precambrian basement, internally intact but tilted and faulted. These represent remnants of the caldera floor that subsided during chamber evacuation, not disaggregated megabreccia lenses. This reinterpretation strengthens the case for large-scale caldera-style subsidence in the SMZ, with preservation of coherent roof blocks amidst ignimbrite and debris-flow fill.

Holohan *et al*. (2009) propose a distinct evolutionary sequence. Injection of magma into a shallow chamber causing doming of the roof, uplifting basement blocks and generating steep, unstable slopes. Mass-wasting of these slopes produced debris-flow and stream-flow breccias that accumulated in local depressions. Subsequently, explosive rhyodacitic eruptions generated pyroclastic density currents that spread across this rugged surface, depositing thick ignimbrite sheets. As the chamber was partially evacuated, structural subsidence occurred, tilting basement slabs downward into the caldera. The result is a stratigraphy that alternates between sedimentary breccias and ignimbrites, recording cycles of uplift, eruption, and collapse within a single structural setting; the SMZ exemplifies the coupled operation of tectonic, sedimentary, and volcanic processes in the caldera system.



Figure 9-198: Glen Dibidil, SE Rum, with (left-to-right): Sgurr nan Gillean (dominated by rhyodacite volcanic rocks), Trollaval (dominated by Phase 2 layered ultrabasic rocks) and Beinn nan Stac (composed of Torridonian strata, with a cap of rhyodacite volcanic rocks). The sea cliffs are composed of Torridonian strata. View towards the west. [Photograph courtesy of Valentin Troll]

Draft version



Figure 9-199: Glen Dibidil, SE Rum, with: Sgurr nan Gillean (left of Glen Dibidil; dominated by rhyodacite volcanic rocks) and Beinn nan Stac (right of Glen Dibidil; composed of Torridonian stata, with a cap of rhyodacite volcanic rocks). The sea cliffs are composed of Torridonian strata. View towards the NW.

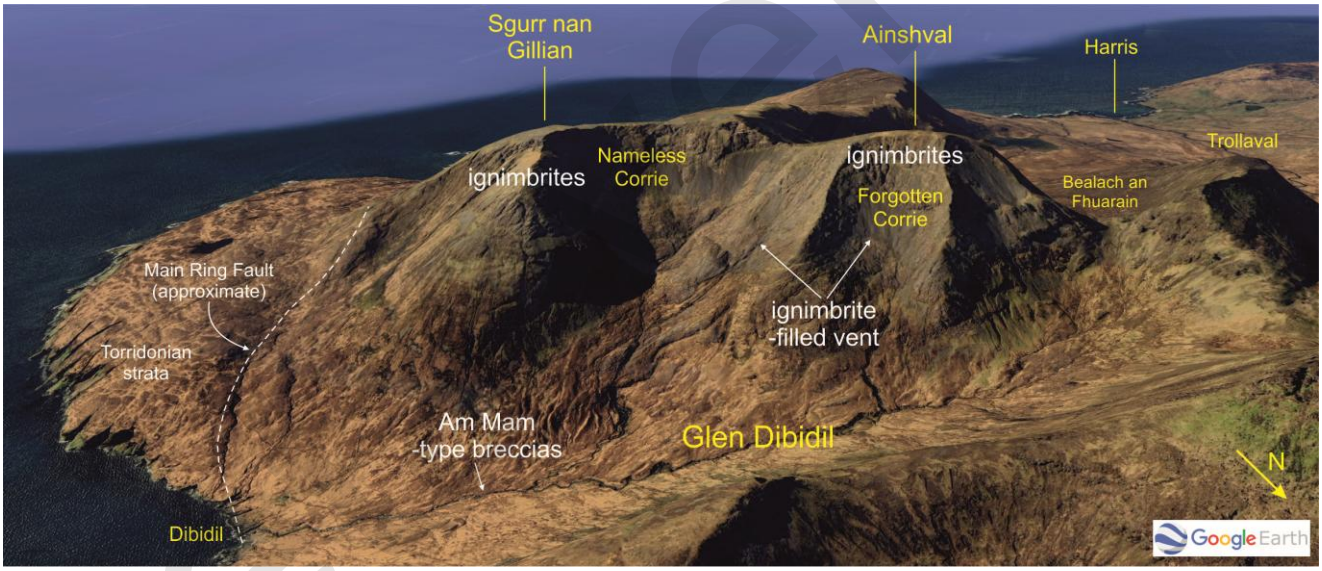
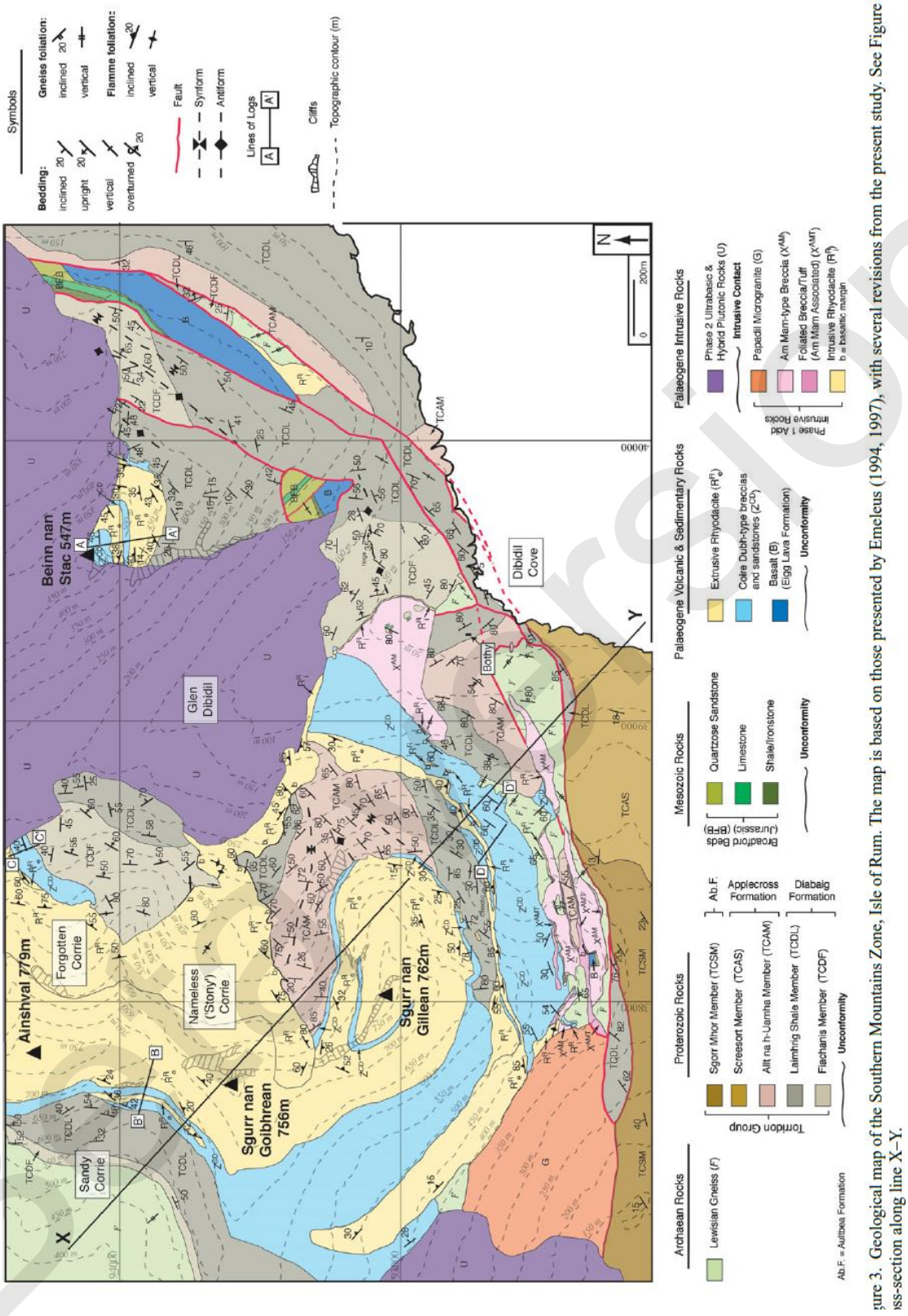


Figure 9-200: Inclined Google Earth© image of the Southern Mountain Zone, SE Rum, indicating location of 'erupted' ignimbrite(s) and vent-fill ignimbrite.

Be



gure 3. Geological map of the Southern Mountains Zone, Isle of Rum. The map is based on those presented by Emeleus (1994, 1997), with several revisions from the present study. See Figure 9 for ss-section along line X–Y.

Figure 9-201: Geological map of the Southern Marginal Zone (NMZ), SE Rum. [Figure courtesy of Eoghan Hologhan, from Hologhan *et al.* 2009]

Borgersen



Figure 9-202: The Sgùrr nan Gillian – Ainshval ridge, SE Rum, viewed looking south, composed of pale 'erupted' and vent facies ignimbrites.



Figure 9-203: The summit of Sgùrr nan Gillian, SE Rum, composed of pale 'erupted' ignimbrites.

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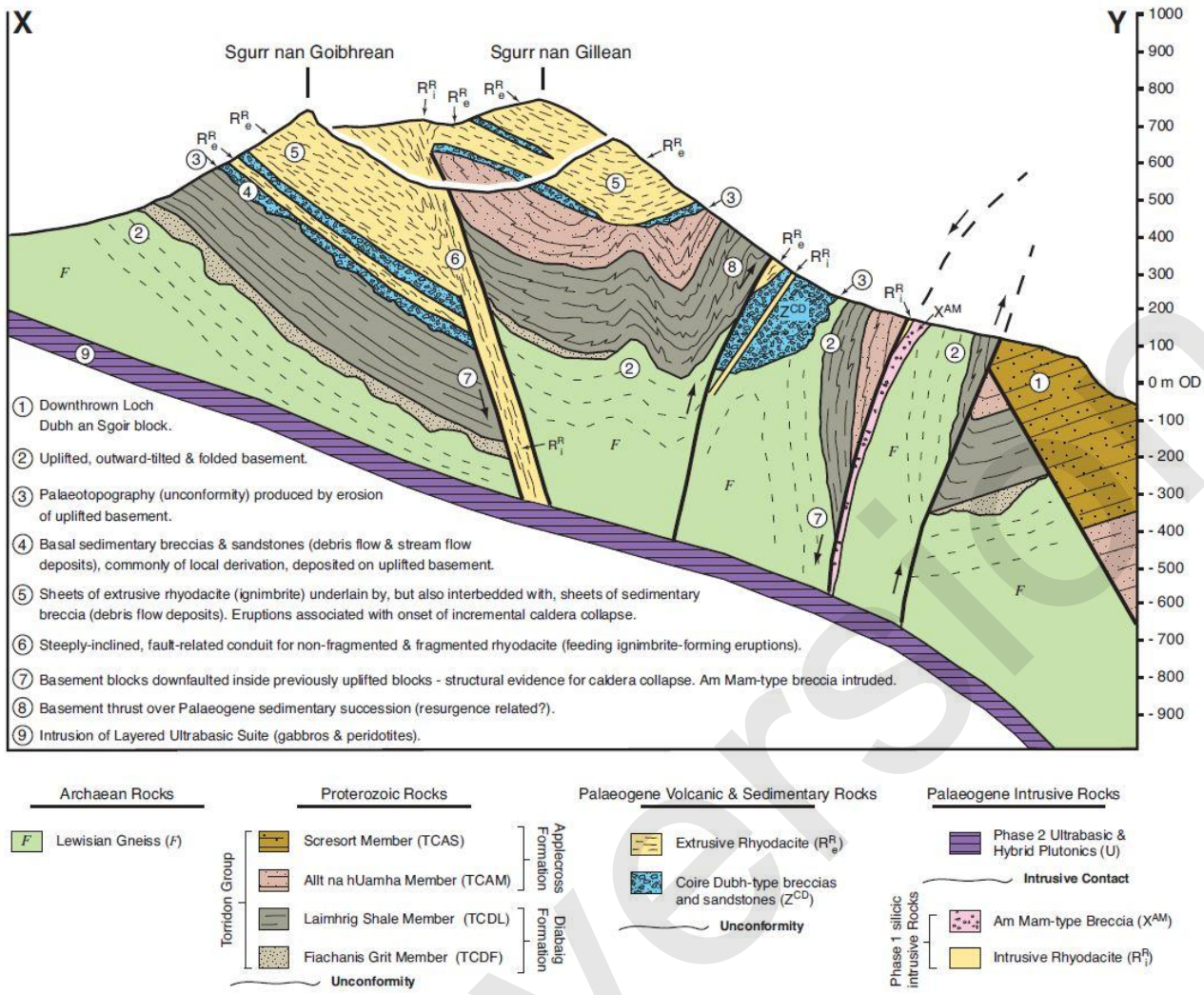


Figure 9-204: Geological cross-section of the Southern Marginal Zone (SMZ). [Figure courtesy of Eoghan Hologhan, from Hologhan *et al.* 2009]

9.9.5 Province-wide implications of observations in the NMZ and the SMZ of Rum

The recent reinterpretations of the rock units within the NMZ and the SMZ carry HIP-wide significance. Within the Province, many silicic units originally identified as intrusive sheets or lavas are increasingly recognised as ignimbrites, and breccias once described as explosive 'intrusive' material are now understood as mass-flow deposits (see Chapter 6). The SMZ provides one of the clearest examples of this paradigm shift and demonstrates that Rum, often regarded as dominated by intrusive rocks, also preserves major silicic pyroclastic deposits. The recognition of an ignimbrite vent within the SMZ directly links the rhyodacite sheets to eruptive processes and establishes parts of Rum as a caldera complex. Comparisons can be drawn with well-studied modern systems where chamber inflation, slope failure, ignimbrite eruption, and subsidence occur in sequence, such as Taupo in New Zealand or large calderas in the Basin and Range Province, USA. The SMZ represents an ancient analogue, offering a static but exceptionally well-preserved record of the same processes.

Integration with the broader magmatic history of Rum strengthens this conclusion. Early silicic activity produced mixed-magma breccias such as the Am Màm intrusion breccia(s), where dacitic melts mingled

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with basaltic material and incorporated fragments of basement material. Recognition that the NMZ and SMZ rhyodacites are ignimbrites demonstrates that silicic magmas did not only intrude but also erupted explosively, generating voluminous pyroclastic deposits that shaped the caldera topography. This dual role of silicic magmas, both intrusive and extrusive, is key for understanding the evolution of the complex and the dynamics of magma chambers in the province.

The SMZ is perhaps best understood as a volcano-sedimentary record of chamber-roof dynamics. Breccias record slope failures triggered by uplift; ignimbrites record explosive eruptions from silicic vents; coherent basement blocks record subsidence of the caldera floor. Together, they form a succession that encapsulates the life cycle of a shallow chamber subject to repeated inflation and evacuation. The conclusions of Holohan *et al.* (2009) supersede earlier models of cryptic explosions and intrusive sheets (Hughes 1960), replacing them with a framework that integrates tectonic deformation, mass-wasting, pyroclastic deposition, and collapse.

9.9.6 Caldera Initiation

The substantial thickness of collapse breccias that accumulated prior to any volcanic activity in the Rum caldera is notable, as is the observation that the earliest tuffs within these breccias make up only a very small portion of their total thickness (Figure 9-205). These findings run counter to the classic model of cauldron subsidence by Williams (1941) and Smith & Bailey (1968), which posits that caldera collapse occurs because of magma withdrawal from a subterranean chamber and that the thickness of volcanic deposits should approximately correspond to the extent of structural collapse. Instead, the evidence from Rum points to an initial phase of caldera collapse occurring *without* significant volcanic eruptions. This suggests that the underlying magma chamber was still expanding due to the ongoing influx of magma (Figure 9-206).

The presence of the first thin tuff layers, along with minor amounts of juvenile magmatic material found above them, indicates that the underlying silicic magma body occasionally erupted small amounts of pyroclastic material. However, following this, there appears to have been a period of quiescence, with no evidence of further collapse or eruptions. During this time, coarse-grained sandstones were deposited, likely by sorting of fines from the breccia deposits.

Volcanic activity then resumed. This new phase began with the eruption of pyroclastic fall and flow deposits, locally preserved as bedded lithic tuffs. This was followed by the emplacement of substantial rhyodacite ignimbrites (Figure 9-205).

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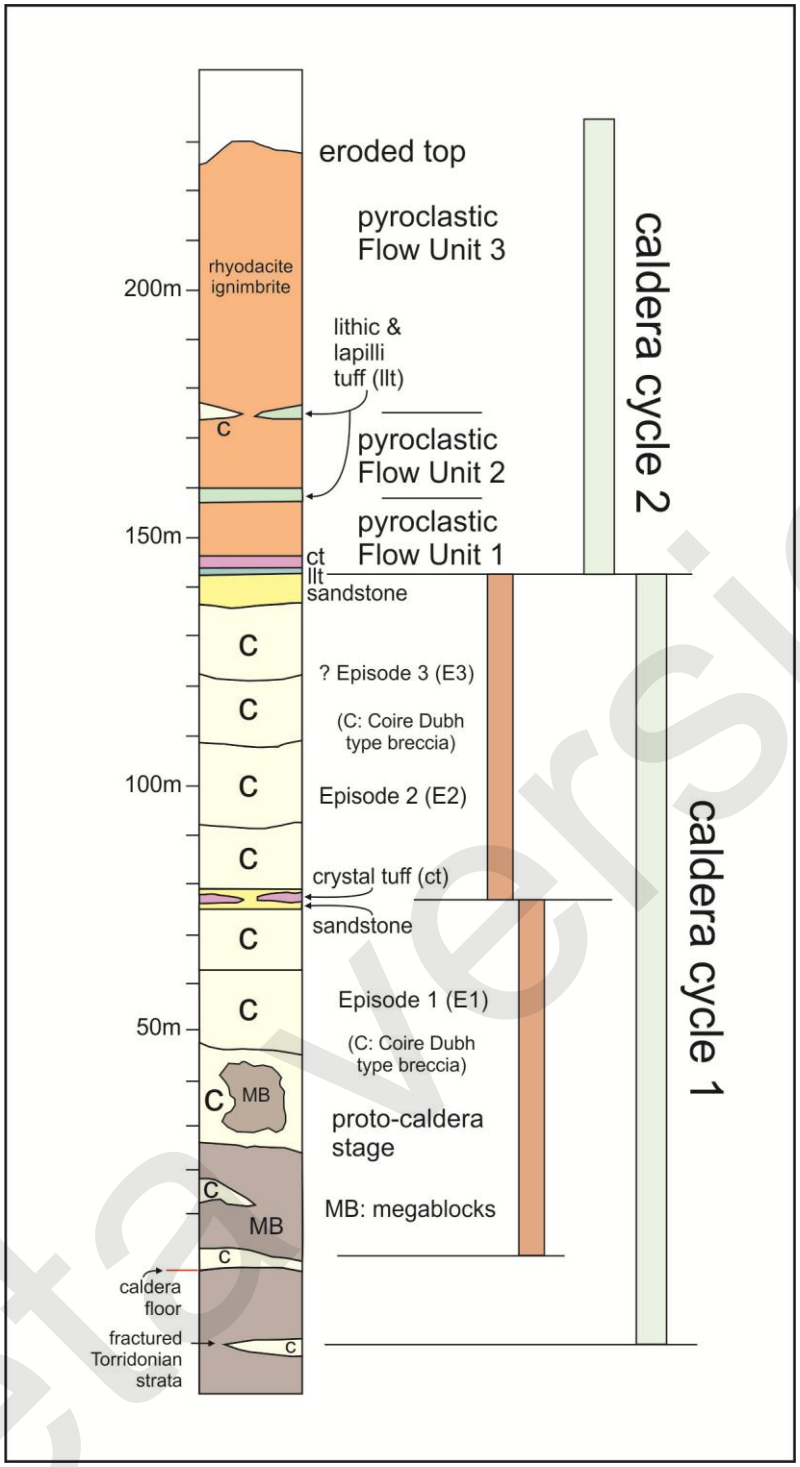


Figure 9-205: Representative log for volcanic sequence in Coire Dubh, Northern Marginal Zone, Rum (after Troll *et al.* 2000).

The first major eruption in the NMZ appears to have been triggered by the intrusion of basaltic magma into the rhyodacite chamber (Figure 9-206). Evidence for this includes the presence of mixed-rock enclaves (inclusions) (Donaldson *et al.* 2001): fine-grained basic rock fragments ranging from 1 to 20 cm in diameter. Two distinct types of enclaves are identified. The first type is aphyric, cryptocrystalline, dark, and andesitic to basaltic in composition, and occurs as blobs, streaks, or schlieren. The lobate and embayed shapes of these inclusions suggest a liquid–liquid interaction with the host rhyodacite, with the basaltic material quenching during eruption. The second type of enclave also consists of basic material, but has chilled margins against the surrounding rhyodacite. These are interpreted as fragments of basaltic

Beta version

melt that were injected into the rhyodacite chamber and solidified against the cooler host magma. Some of these enclaves contain flattened vesicles, indicating gas escape. It is likely that gas released from the basaltic magma, along with gas exsolved from the rhyodacite due to heating by the injected basalt, triggered the subsequent explosive ignimbrite-forming eruptions (Figure 9-206).

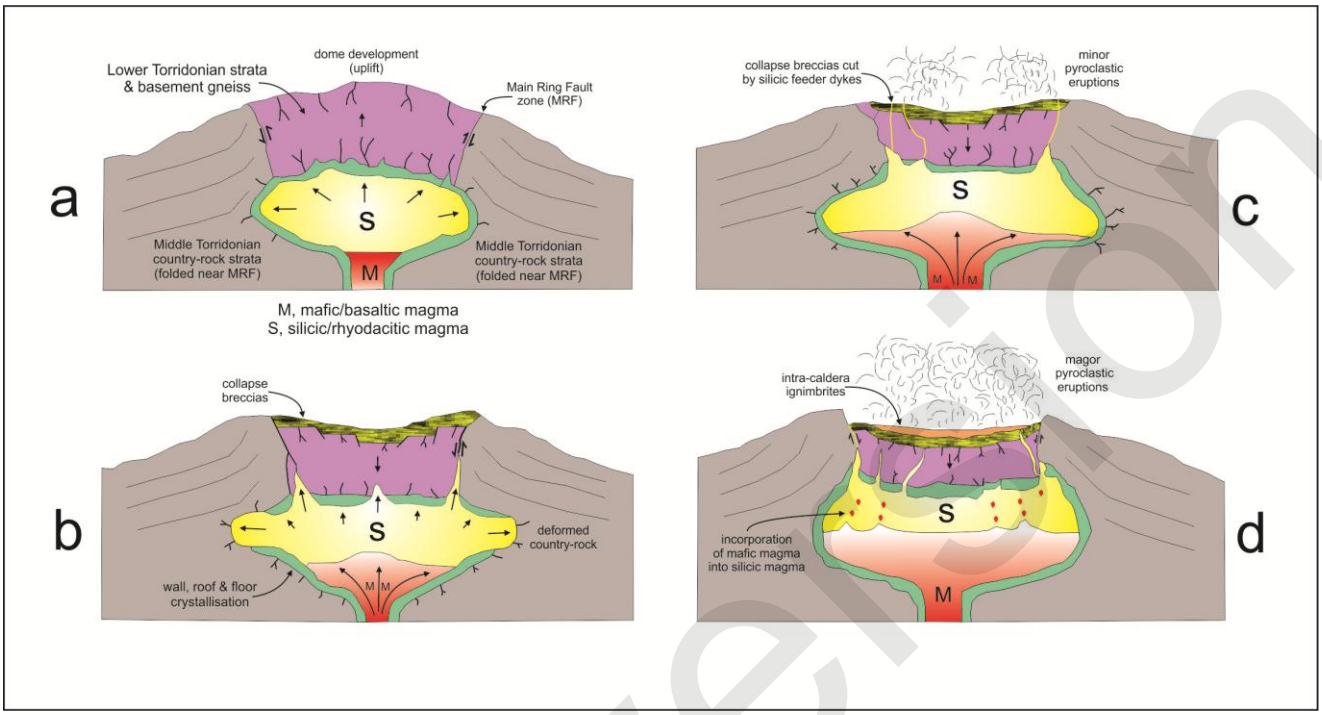


Figure 9-206: Model for the evolution of the Rum caldera: (a) doming results in ring fracture formation (MRF) and uplift of Lewisian basement gneiss and overlying Lower Torridonian strata (uplift estimated at > 1 km); (b) formation of collapse structure as a result of magmatic tumescence and/or chamber growth which induces tensile stress in the overburden, with proto-caldera formation without accompanying eruptions until up to 70 m of breccia has accumulated; (c) caldera resurgence following a period of quiescence, with silicic magma (S, rhyodacite) exploiting a new fracture system not exclusively along the Main Ring Fracture (MRF) zone, with eruption triggered by a replenishment of the feeder system by fresh mafic (M, basaltic) magma; (d) eruption of rhyodacitic magma leading to caldera collapse into partially emptied magma chamber. (after Troll *et al.* 2000).

On the NE side of Dibidil and on the eastern slopes of Beinn nan Stac, SE Rum, slivers of Lower Jurassic (Broadford Beds Formation) limestone, siltstone and sandstone, and of altered basaltic lava derived from the Eigg Lava Formation (Chapter 6), owe their preservation to subsidence within the Main Ring Fault.

However, the final event of Phase1 involved further uplift on the Main Ring Fault system, when Torridon Group sandstones were reverse faulted over the Mesozoic sedimentary rocks and Paleocene lavas on the eastern slopes of Beinn nan Stac (Figure 9-207). In western Rum, granite (see below) was similarly faulted over sandstones of the Torridon Group near Bloodstone Hill. This late uplift is tentatively attributed to the forcible emplacement of the silicic magma that formed the Western Granite.

Beta version



Figure 9-207: Glen Dibidil, SE Rum, with, to the north (left) Beinn nan Stac, capped with a thrusted sheet of Torridonian strata overlain by Paleocene volcanic rocks, mainly breccias and rhyodacite ignimbrite. In the distance is the island of Eigg.

9.9.7 The Western Granite

The Western Granite and similar smaller granite bodies near the Long Loch and Papadil postdate the rhyodacite ignimbrites. This well-jointed intrusion is magnificently exposed in cliffs and raised-beach platforms in west Rum, although inland exposure is poor (Figure 9-208; Figure 9-209). The granite is micro-porphyritic and of similar composition to the porphyritic rhyodacites of the NMZ and the SMZ (see above). It contains phenocrysts of plagioclase, together with ferroaugite and ferropigeonite, both of which are generally partially altered to amphibole. A small area of granophyric granite containing micro-phenocrysts of fayalite and ferroaugite, as well as plagioclase, crops out on the SE slopes of Sròn an t-Saighdeir. Magnetic petrofabrics within the Western Granite indicate that it is most likely a remnant of a shallowly emplaced tabular sheet and possibly an intrusive equivalent of the rhyodacite ignimbrites.

Beta version



Figure 9-208: Oblique Google Earth© image of the west coast of Rum at A' Bhrìdeanach, composed of the Western Granite. The hill, beyond, is Sròn an t-Saighdeir. View towards the SE.



Figure 9-209: View of the west coast of Rum, SE of Wreck Bay, composed of the Western Granite.

Review version

9.9.8 Phase 2: The layered ultrabasic and basic rocks of the Central Complex

9.9.8.1 Introduction

Basaltic and picritic ('ultrabasic') magmatism predominated throughout Phase 2. Initially, numerous basaltic dykes were intruded, accompanied by many inclined sheets (cone-sheets), which are present throughout the Northern Marginal Zone and Southern Mountains Zone. The cone-sheets focus on a point at depth beneath upper Glen Harris; unlike the cone-sheets of the Cuillin Intrusive Centre on Skye (see above), those on Rum are fine grained, possibly reflecting emplacement at a shallower level. The principal trend of the basaltic dykes is NW-SE, and they merge with the regional Muck Dyke Swarm (Chapter 7). Additionally, there are many dykes that trend N-S or NNE-SSW so that, overall, the dykes define a radial pattern, as was noted by Harker (1908). In SW Rum, several generations of approximately NW-trending dykes intrude the Western Granite but few extend into the layered intrusions.

The greatest development of basic and ultrabasic rocks is in the layered intrusions, which crop out over much of the high ground of the central, eastern and southern parts of the island (Figure 9-210; Figure 9-211; Figure 9-212; Figure 9-213; Figure 9-214; Figure 9-215; Figure 9-216; Figure 9-217; Figure 9-218; Figure 9-219; Figure 9-220; Figure 9-221; Figure 9-222). These intrusions postdate the cone-sheets and most of the dykes. Many of the layered structures are identical with, and of similar origin to, those in the Cuillin Intrusive Centre of Skye (see above). These rocks are referred to as the Rum Layered Suite and comprise three distinct 'sequences': the Eastern Layered Intrusion (ELI), the Western Layered Intrusion (WLI) and the Central Intrusion (CI). In eastern Rum, the classic layered rocks (Harker 1908; Brown 1956; Wager & Brown 1968) are intruded by numerous semi-concordant sheets of gabbro, for example in Atlantic Corrie and on Askival, where they accentuate the stratified character of the exposures (Volker & Upton 1990). The layered rocks are also cut by plugs of gabbro and feldspathic peridotite, as are earlier members of the central complex and the country-rocks (see also below).

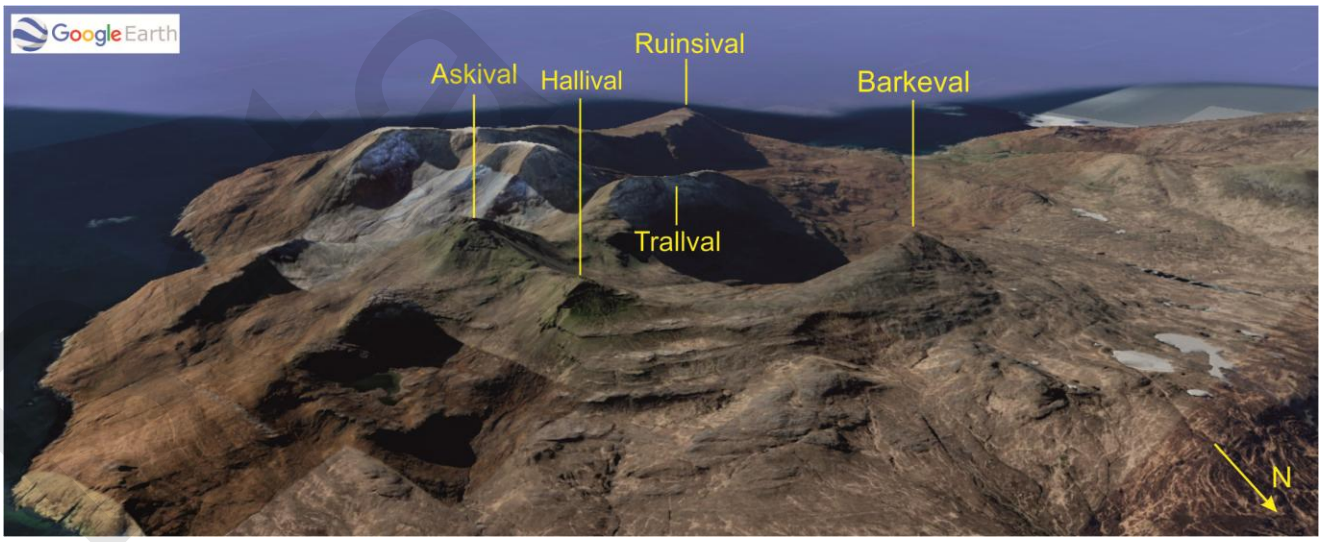


Figure 9-210: Oblique Google Earth© image of eastern and southern Rum, illustrating the stratified character of the ultrabasic rocks that crop out on Askival, Hallival and Barkeval, constituting the Eastern Layered Intrusion. View towards the SW.

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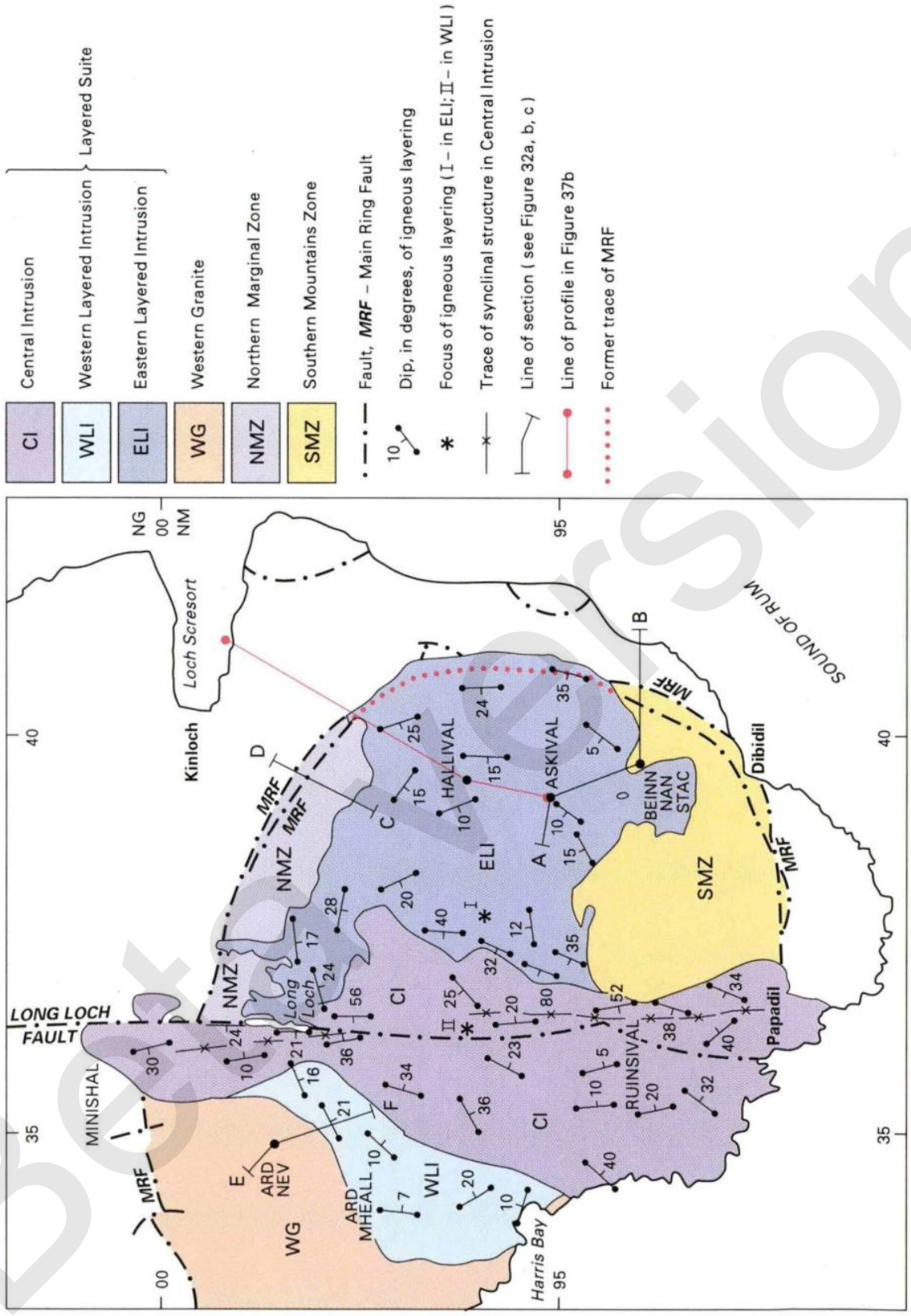


Figure 9-211: Structure of the Rum Layered Suite, comprising the Eastern Layered Intrusion, the Western Layered Intrusion and the Central Intrusion (after Emeleus 1997).

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Figure 9-212: Hallival viewed from Askival, towards the north, with the Cuillin of Skye in the distance. [Photograph courtesy of David Brown]



Figure 9-213: Hallival viewed from Askival. [Photograph courtesy of David Brown]

Review



Figure 9-214: Hallival viewed towards the west. [Photograph courtesy of David Brown]



Figure 9-215: Beinn nan Stac, Askival and Hallival (left-to-right) viewed towards the west from the Sound of Rum. [Photograph courtesy of David Brown]

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Figure 9-216: Barkeval, Hallival and Askival (left-to-right) viewed towards the east from Loch an Dornabac. [Photograph courtesy of David Brown]



Figure 9-217: Barkeval, Hallival, Askival and Trallval (left-to-right) viewed towards the east from Loch an Dornabac. [Photograph courtesy of David Brown]



Figure 9-218: Hallival, Askival, Trallval and Sgùrr nan Gillian (left-to-right) viewed towards the east from Loch an Dornabac. [Photograph courtesy of David Brown]

Beta version



Figure 9-219: Barkeval, Hallival, Trallval, Sgùrr nan Gillean and Ruinsival (left-to-right) viewed towards the NE from off south Rum.



Figure 9-220: Ruinsival from Harris Bay, with the Bullough Mausoleum in the foreground. [Photograph courtesy of David Brown]

9.9.8.2 The Eastern Layered Intrusion (ELI)

The Eastern Layered Intrusion (ELI) (Brown 1956; Wager & Brown 1968; Volker & Upton 1990) comprises the classic layered sequence of 'paired' feldspathic peridotites and bytownite troctolites that is at least 700 m thick (Figure 9-221; Figure 9-222). These rocks form much of the high group of east Rum, including the pyramidal peaks of Askival and Hallival, together with Barkeval, Trallval, Ruinsival, and much of the ground west of Beinn nan Stac (but not the summit). The ELI has marginal gabbros, and where these unlayered rocks are in contact with pre-Paleocene country-rocks (predominantly Torridonian strata; Chapter 2) and the older Paleocene Western Granite, there are complex intrusion breccias due to melting and an aureole of high grade (Sanidinite Facies) metamorphic rocks.

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Figure 9-221: Hallival viewed towards the SE. [Photograph courtesy of David Brown]



Figure 9-222: Askival viewed towards the SW (from east of Hallival). [Photograph courtesy of David Brown]

In addition, the layered rocks are intruded by almost conformable sheets ('sills') of gabbro, bytownite-gabbro and bytownite-troctolite, together with gabbro plugs (Emeleus 1997).

The sixteen paired units formed from the base to the top (Emeleus 1997); lateral variation is significant, with the sequences on Trallval being dominated by peridotite (Volker & Upton 1990). The illusionary stratigraphic simplicity of the intrusion is easily demonstrated from comparison of data from geographically dispersed measured profiles (Figure 9-223). Furthermore, the transition between olivine-rich (peridotite) and plagioclase-rich (troctolite) units is in some instances gradational, whereas elsewhere, abrupt; this transition can vary laterally for any one unit. Small- and large-scale reversals in the modal proportions of olivine and plagioclase are also recognised (Faithfull 1985). At a more detailed level, layering due to differing proportions of olivine and plagioclase introduce further complexities.

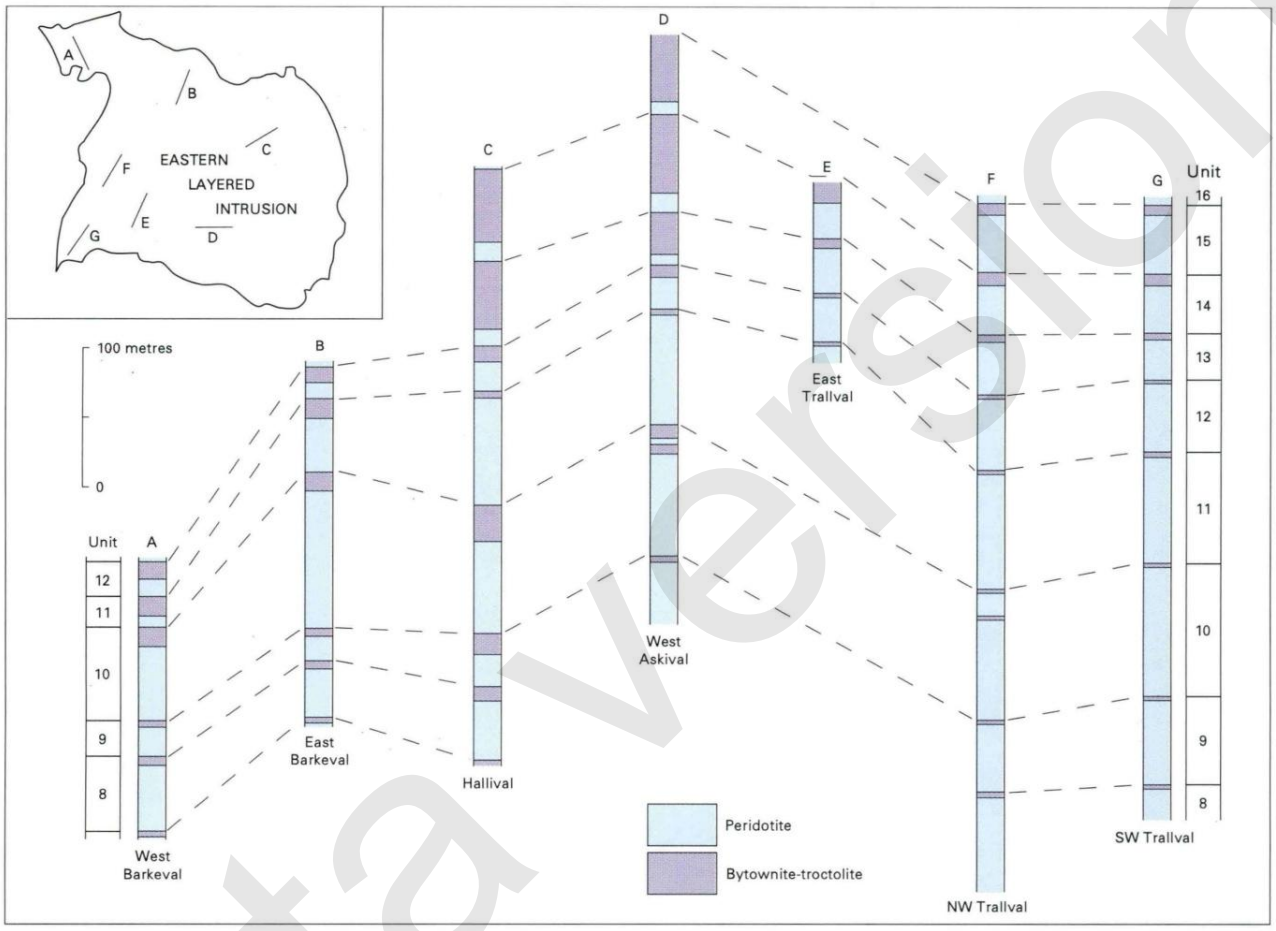


Figure 9-223: Stratigraphic correlation in the Eastern Layered Intrusion, Rum (after Emeleus 1997).

The layering (or stratification) is generally inclined towards the west (Glen Harris) at *ca*. 10-20°, although the inclination is more variable and steeper on Trallval, increasing westward from 12° NNW to 60-80° WNW; Volker & Upton 1990), which may be attributed to the emplacement of the younger Central Intrusion through faulting and slumping.

The estimated thickness of the layered rocks is *ca*. 750 m, with an average thickness of each paired unit of *ca*. 50 m, although ranging between 15 and 150 m (Emeleus 1997). The outer margin of the intrusion is approximately coincident with the main ring fault (Figure 9-211; Figure 9-224). West of the summit of Beinn nan Stac and between Cnapan Breaca and Meall Breac, outward dipping roof contacts are preserved (Greenwood 1987); the intrusion underlies the SMZ and the NMZ west of Meall Breac. A projection of the inclined contact at Beinn nan Stac towards the NNW suggests that the highest units, forming the summit of Askival, were just *ca*. 200 m below the roof of the intrusion (Figure 9-224) (Emeleus 1997).

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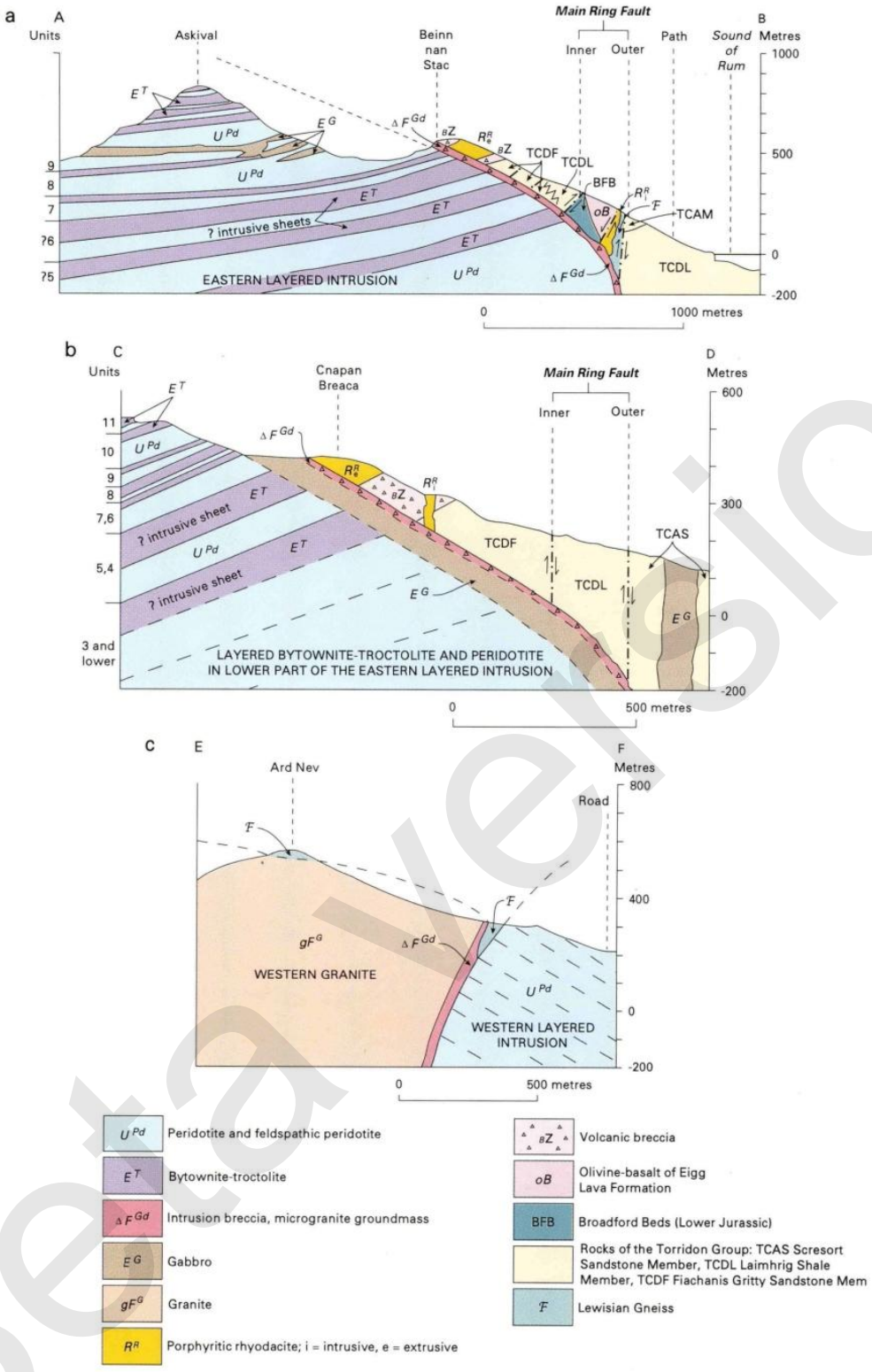


Figure 9-224: Cross-sections through the margins of the Layered Suite, Rum (after Emeleus 1997).

The classic interpretation of the ELI is that the peridotites are an integral basal part of each of the fifteen units recognised by Brown (1956), formed by magmatic 'sedimentation' from picritic magma to produce the so-called igneous cumulates (Figure 9-225). Other features typical of clastic sedimentary rocks are recognised, including: graded bedding, cross stratification, slump structures and various breccias. However, more recently, this wholesale interpretation has been questioned, and various lines of evidence

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have been put forward concerning other processes that may, in part, explain various characteristics of these rocks. For example, the feldspathic peridotite of Unit 9 has been interpreted as a sill within the cumulate sequence (Bédard *et al*. 1988).



Figure 9-225: Modally layered troctolite with small-scale slump structures (centre of image) and peridotite replacing troctolite (near base of 2 m high section), SE Hallival, ELI. [Photograph courtesy of Valentin Troll]

9.9.8.3 The Western Layered Intrusion (WLI)

The Western Layered Intrusion, originally described by Wadsworth (1961) and redefined by Volker (1983), comprises: the Harris Bay Member (structurally/'stratigraphically' lowest); the Transitional Member; and, the Ard Mheall Member (structurally/'stratigraphically' highest). This layered sequence is *ca*. 500 m thick, with the layering dipping gently (10–20°) toward Glen Harris (Figure 9-211). While this structural pattern mirrors that of the ELI, the lithological succession differs. Unlike the ELI, the WLI lacks plagioclase-rich cumulates, making its internal divisions less distinct. The layering in the WLI primarily reflects textural variations rather than changes in mineral composition, although minor modal variation does occur at smaller scales.

The main subdivisions are defined by a compositional transition from the bytownite-gabbro of the Harris Bay Member, upwards into the feldspathic peridotites and peridotites of the Transitional and Ard Mheall members. Layering is common and is marked by alternating coarse-grained 'harrisitic' layers and more equigranular peridotites and gabbroic rocks. Subtler textural differences are also evident in the finer-grained lithologies (Figure 9-226; Figure 9-227).

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Figure 9-226: Upward-growing olivine crystals in harrisitic layers in the Transitional Member, Western Layered Intrusion. Track-side *ca.* 650 m NNW of Harris Lodge. Hammer *ca.* 30 cm long.



Figure 9-227: Elongate, skeletal olivine crystals (up to *ca.* 1 m long) WLI, Harris Bay. Hammer *ca.* 30 cm long. [Photograph courtesy of Valentin Troll]

The contact between the WLI and the Western Granite (see below) is steep, ranging from vertical to outward dipping. This is clearly observed in the cove *ca*. 100 m SW of the Harris Mausoleum and is thought to continue with similar steepness for *ca*. 1.7 km northward into the poorly exposed ground of the lower part of Glen Duian. On the NW slopes of Ard Mheall, the contact is mostly obscured by drift deposits. Between Ard Mheall and the southern to SE slopes of Ard Nev, the peridotites appear to dip beneath a roof composed of Western Granite and an overlying wedge of gneiss (Figure 9-224). A zone of complex intrusion breccia typically marks this contact (Figure 9-228; Figure 9-229).



Figure 9-228: Layered gabbro in the WLI intruded by remobilized ('rheomorphic') silicic veins derived from partial melting of the adjoining (older) Western Granite. The silicic magma has been channelled along planes of weakness provided by the layered structures. East side of Harris Bay. Hammer *ca*. 30 cm long. [Photograph courtesy of Valentin Troll]

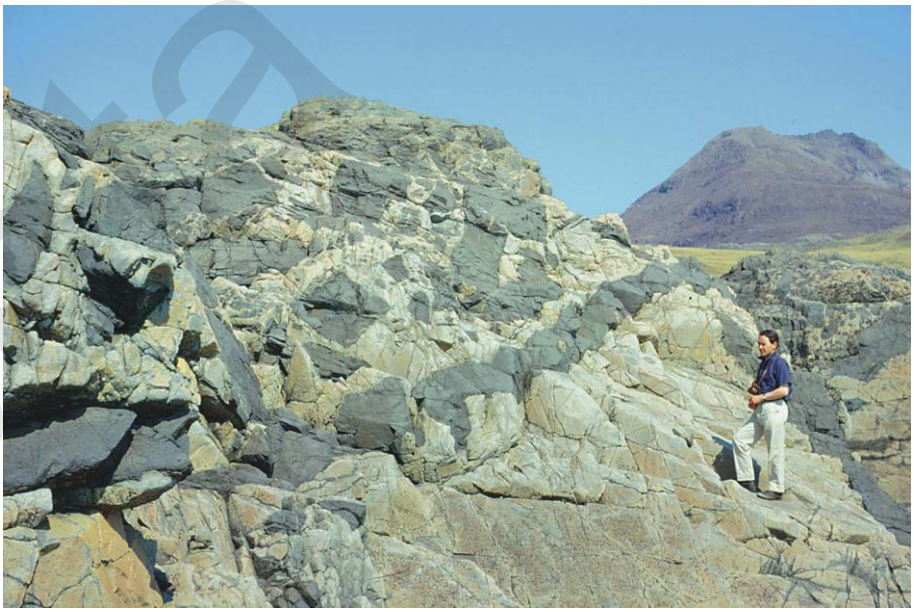


Figure 9-229: Intrusion breccia at margin of the Western Layered Intrusion, SW Rum.

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9.9.8.4 The Central Intrusion (CI)

The Central Intrusion was first identified by McClurg (1982), with its boundaries later defined by Volker (1983) (Figure 9-211; Figure 9-230). It occupies a broad zone extending southward from Minishal to the coastline between Papadil and the eastern side of Harris Bay, cutting across the Western and Eastern Layered Intrusions as well as the Main Ring Fault (Figure 9-231). It comprises thick, layered units of peridotite and bytownite-troctolite, both exhibiting fine-scale internal layering, along with extensive linear zones of ultrabasic breccia. Intrusion-related breccia is also found at several locations along the contact with Torridonian rocks, and where it intersects with the Western Granite at Monadh Mhiltich and Minishal.

[TOP]	
Ruinsival Member:	Two cyclic units, peridotite-rich, the lower one capped by *ca.* 10 m of bytownite-troctolite; *ca.* 330 m thick; restricted to Ruinsival summit area
Long Loch Member:	Three cyclic units, mainly peridotite with thin (< 10 m) bytownite-gabbro at top of each; *ca.* 600 m thick NW of Ruinsival and *ca.* 450 m in lower Glen Harris; forms core of syncline in Central Intrusion west and NW of the Long Loch
Dornabac Member:	150 m+ thick, but base not exposed; consists of thick bytownite-troctolite; well exposed at An Dornabac, but thins northwards; underlain by peridotite
[BASE]	

Figure 9-230: Members of the Central Intrusion, Rum.



Figure 9-231: Central Intrusion rocks forming Barkeval, Trallvall and Ruinsival (left-to-right) viewed towards NE from off south Rum.

Structurally, the Central Intrusion is complex. The small-scale layering within the bytownite-troctolites closely resembles that observed in the Eastern Layered Intrusion; for example, in outcrops on the ridge

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ca. 150 m NW of the northern end of the Long Loch (Figure 9-232; Figure 9-233). Although a layered sequence is present (Figure 9-230; Figure 9-234), it is disrupted by multiple linear zones of ultrabasic breccia (Wadsworth 1961, 1992; Volker & Upton 1990). Near Long Loch, these breccia zones trend roughly N-S, but they become more numerous and fan out further south of Loch Fiachanis (Volker & Upton 1990). Breccia also occurs along the contact with the WLI and, to a lesser extent, the ELI.

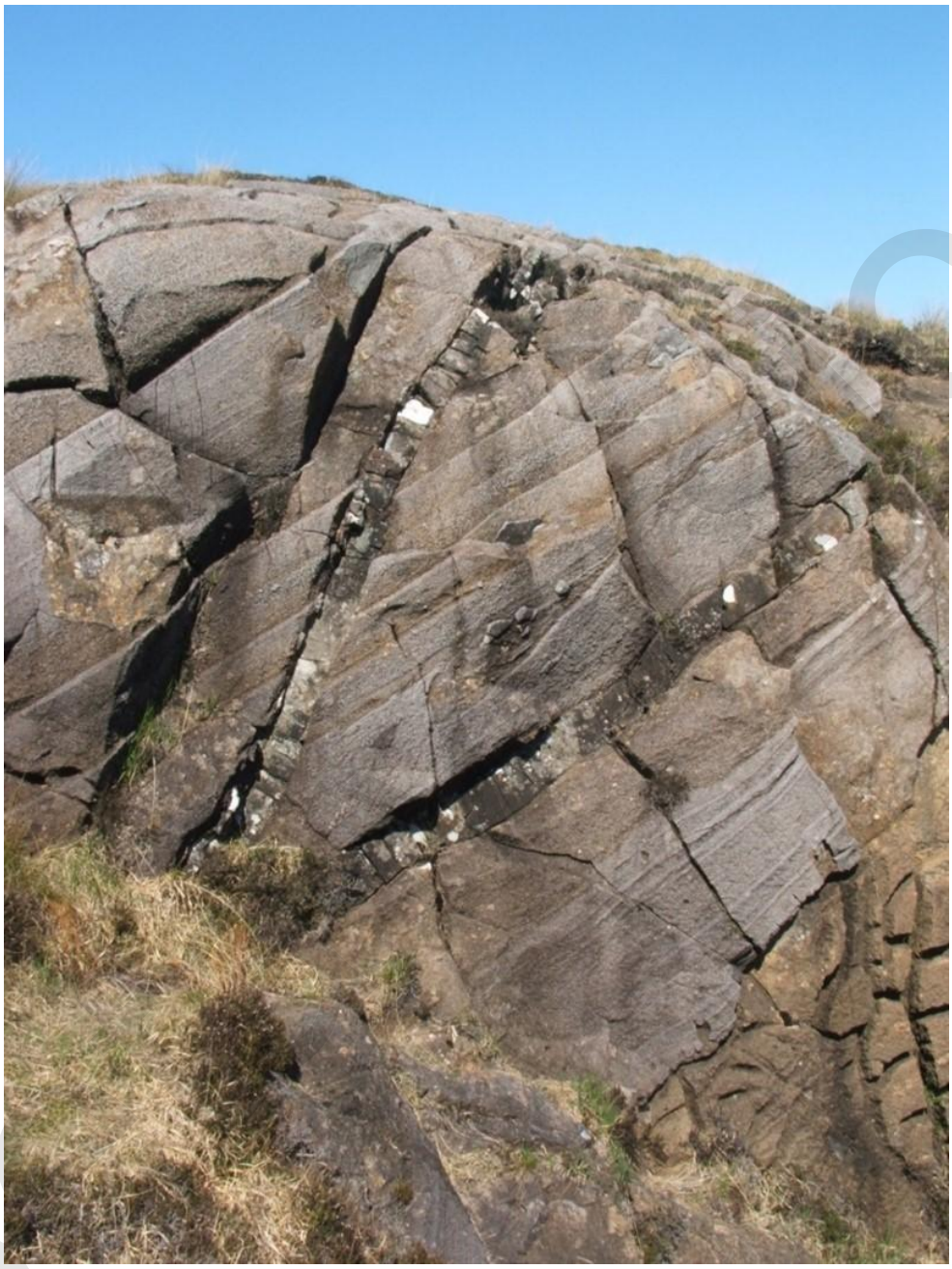


Figure 9-232: Graded layering cut by dykes, and slumps and anorthosite clasts between the two dykes. Long Loch Member, Central Intrusion. Whaleback ridge west of Long Loch.



Figure 9-233: Detail of graded layering cut by dykes, Long Loch Member, Central Intrusion. Whaleback ridge west of Long Loch.

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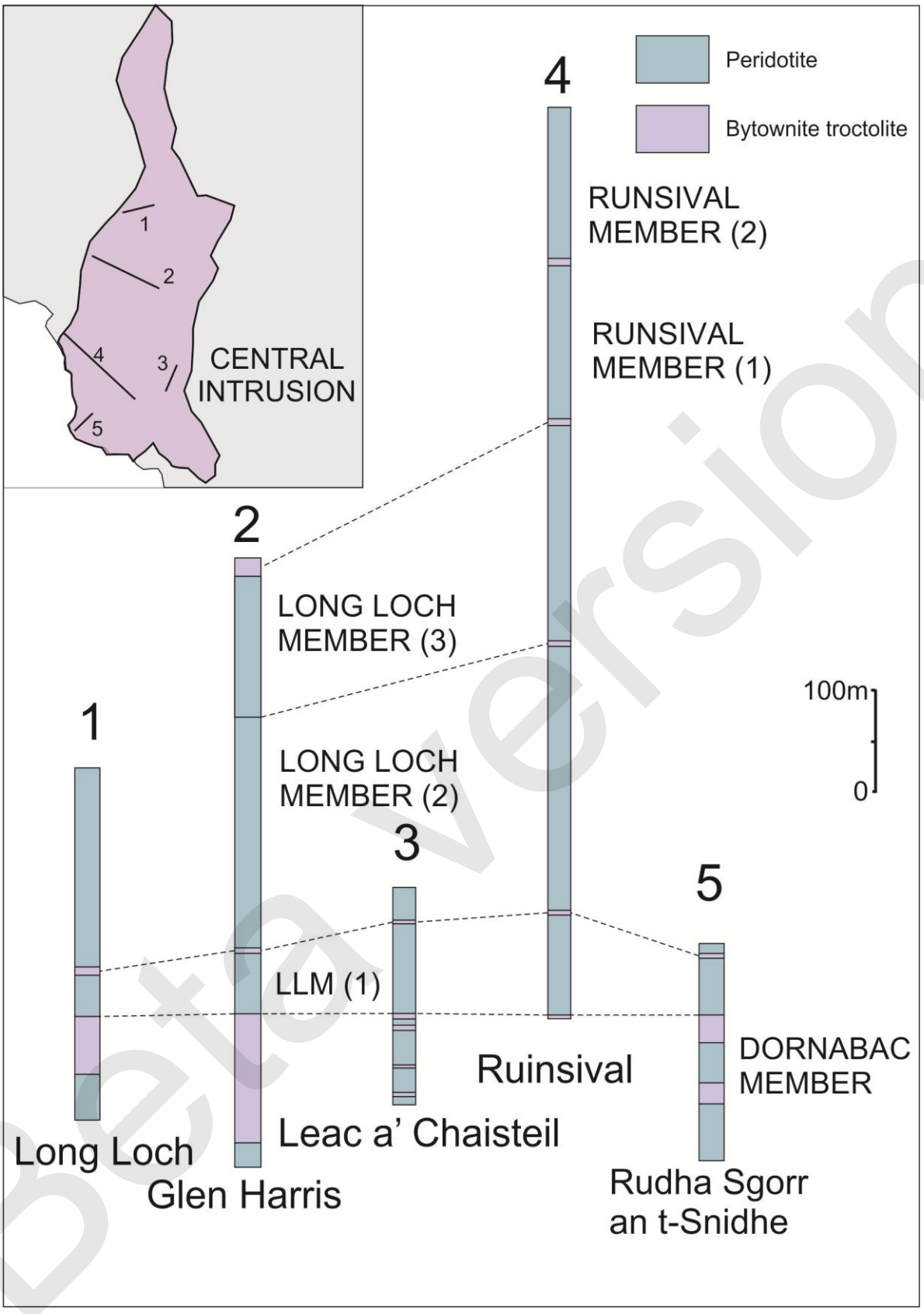


Figure 9-234: Stratigraphic correlation for the Central Intrusion (after Emeleus 1997).

The internal layering within the Central Intrusion dips between 20° and 60°, striking approximately N-S and forming a broad, shallow syncline that stretches from west of Long Loch to Ruinsival (Figure 9-211; Figure 9-235; Figure 9-236). The steeper dips are likely of tectonic origin, as bytownite-troctolite and bytownite-

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gabbro tend to develop soft-sediment deformation structures on slopes exceeding 20°. According to Volker & Upton (1990), there was a complex interplay between bytownite-troctolite accumulation and breccia formation (Figure 9-235; Figure 9-236). During tectonically stable periods, evolved intercumulus liquids expelled from large bodies of unconsolidated olivine cumulates crystallised to form bytownite-troctolite. However, during episodes of tectonic extension, fractures formed within the still-unconsolidated olivine-rich cumulates, allowing evolved liquids and fragments from already solidified sections to fill the voids, producing the linear breccia zones.

The intrusive nature of the Central Intrusion is also evident at outcrop scale. For instance, Central Intrusion breccias cut through well-layered peridotites of the Ard Mheall Member of the WLI. From *ca*. 250 m NNE to *ca*. 400 m SE of the southern tip of Long Loch, breccias intrude bytownite-troctolite and peridotite of the ELI, as well as an earlier tongue of peridotite. On the NW slopes of Trallval, *ca*. 300 m west to NW of Triangular Buttress, a marginal olivine-gabbro and breccias from the Central Intrusion cut into the highest units of the ELI.



Figure 9-235: Contact between pale troctolite (right) and ultrabasic breccia (left) of Long Loch Member, Central Intrusion. NW of Long Loch, pole *ca*. 1 m long.

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Figure 9-236: Peridotite blocks ('dropstones') in troctolite of Long Loch Member, Central Intrusion. NW of Long Loch, pole *ca.* 1 m long.

The external contacts of the Central Intrusion are typically vertical or steeply inward-dipping, such as on Trallval and the western side of An Dornabac, where Central Intrusion olivine-gabbro overlies peridotites of the Ard Mheall Member of the WLI (Figure 9-211; Figure 9-224).

9.9.9 Minor structures in the layered rocks

9.9.9.1 Introduction

Small-scale structures are a characteristic feature of the layered peridotites, and especially of the bytownite-troctolites. These include a diverse array of features analogous to those observed in both subaqueous and subaerial sedimentary environments (Wadsworth 1973). Some structures resemble those formed by soft-sediment deformation (Volker 1983; Volker & Upton 1990), whereas others result from metasomatic replacement processes operating within the layered sequences.

The most widespread and visually prominent feature in the Layered Suite is the regular small-scale layering (Figure 9-237; Figure 9-238), commonly referred to as rhythmic layering. This layering is analogous to bedding in sedimentary rocks and consists of laminae (<1 cm thick) or thicker layers (>1 cm), distinguished by contrasts in mineralogy and/or texture. Although these contrasts can be subtle, they are often accentuated by differential weathering. The variations primarily reflect differences in modal proportions and textural relationships among olivine, plagioclase and clinopyroxene. Less frequently, but very distinctively, thin laminae (1–5 mm) rich in euhedral chrome spinel crystals are present. These chromite-rich layers are commonly laterally continuous and typically occur at the lower boundaries of peridotite layers in contact with bytownite-troctolite or anorthositic rocks (Brown 1956) (Figure 9-239;

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Figure 9-240; Figure 9-241; Figure 9-242). However, they also occur within peridotite and anorthositic bytownite-troctolite (McClurg 1982). Small-scale irregularities resembling sedimentary load casts are also relatively common (Figure 9-243).

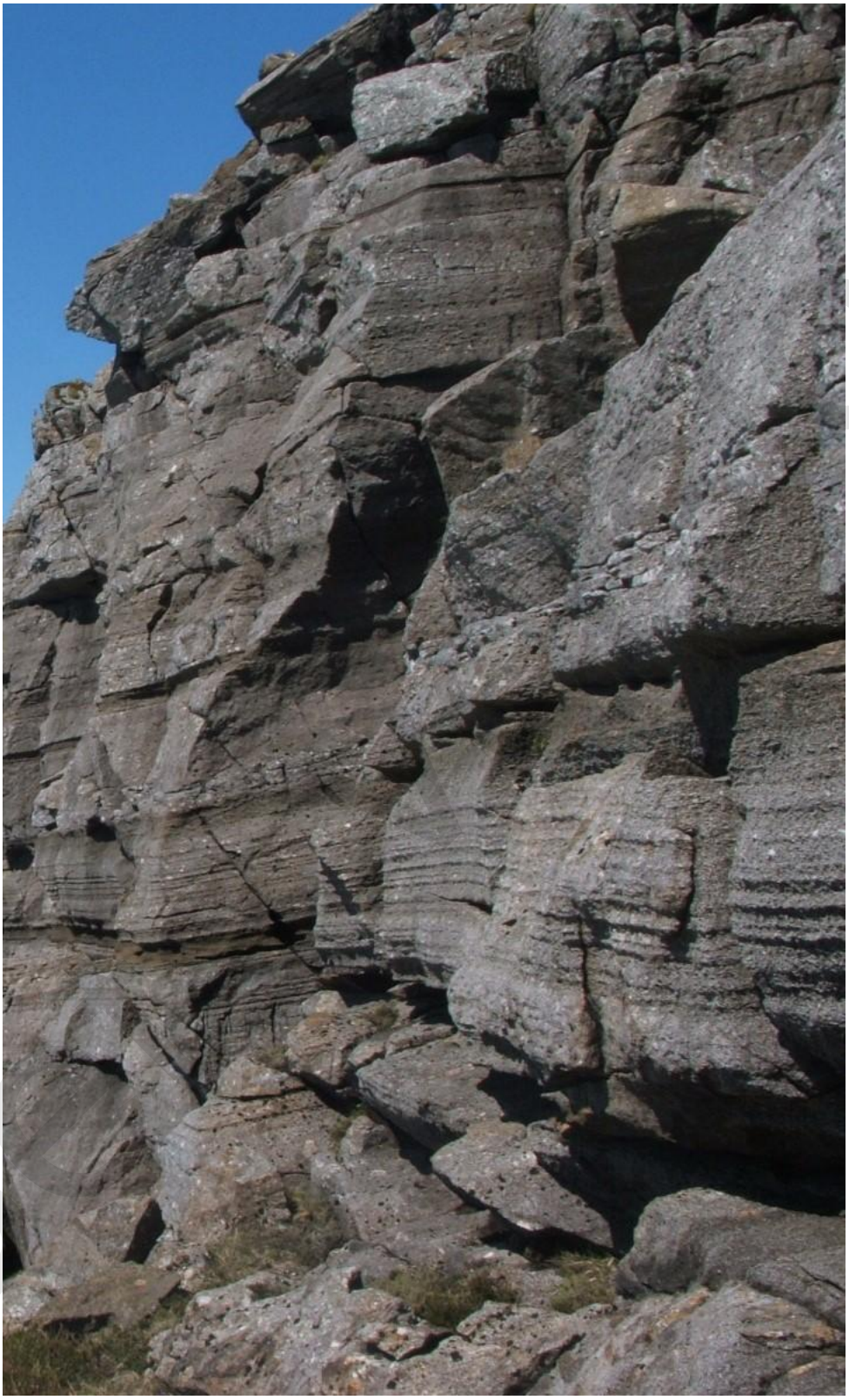


Figure 9-237: Small scale rhythmic layering, Eastern Layered Intrusion, west Hallival. [Photograph courtesy of David Brown]

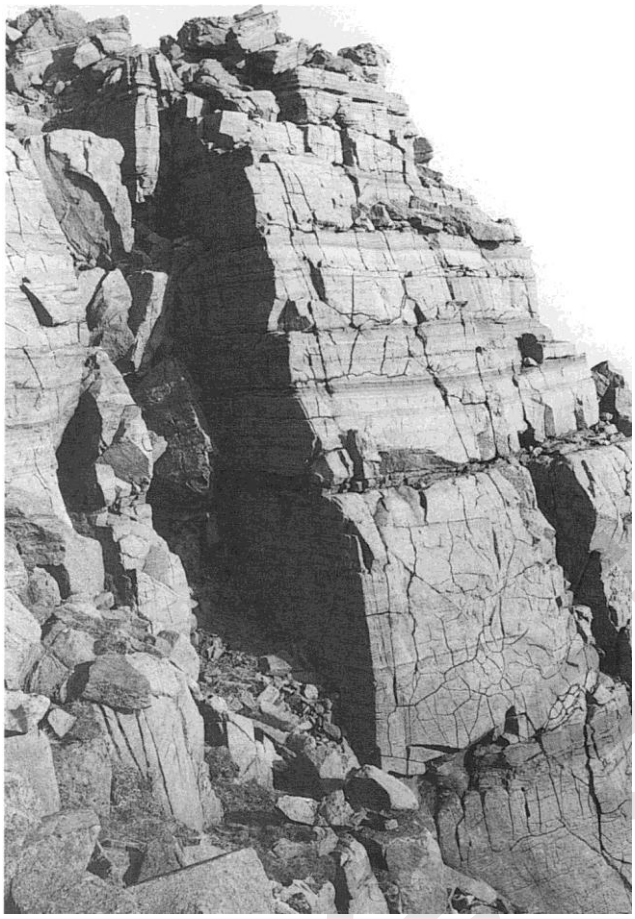


Figure 9-238: Small scale rhythmic layering in Unit 13, Eastern Layered Intrusion, SE Askival. [Photograph courtesy of Henry Emeleus]



Figure 9-239: Chromite seam(s) along the boundary between pale anorthositic troctolite and dark peridotite at the base of Unit 8 of the Eastern Layered Intrusion, Bealach Bairc-mheall (between Barkeval and Hallival). Hammer *ca.* 30 cm long. [Photograph courtesy of Valentine Troll]

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Figure 9-240: Chromite seam(s) along the boundary between pale anorthositic troctolite and dark peridotite at the base of Unit 8 of the Eastern Layered Intrusion, Bealach Bairc-mheall (between Barkeval and Hallival). [Photograph courtesy of David Brown]

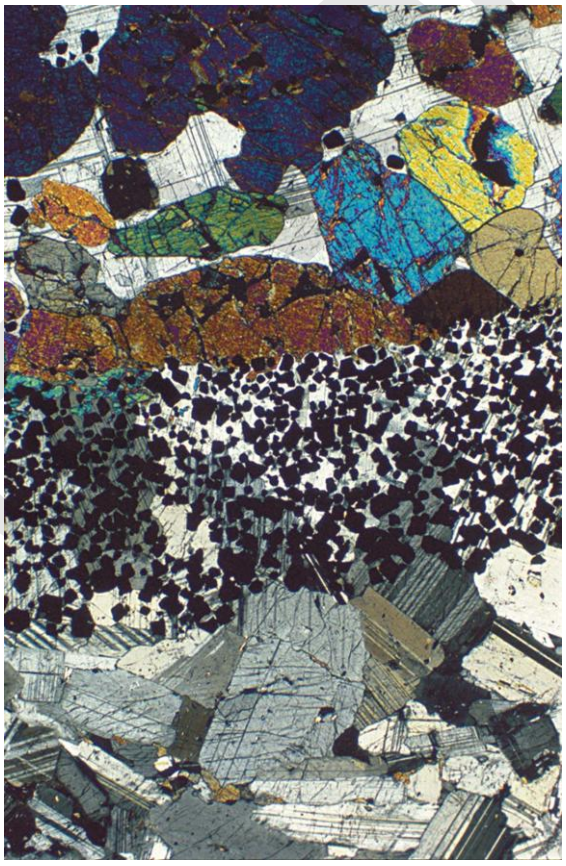


Figure 9-241: Chromite-rich seam at contact between anorthositic bytownite-troctolite (an extreme plagioclase-dominated cumulate) of Unit 11 (below) and feldspathic peridotite of Unit 12 (above), NE Hallival. [Photograph courtesy of Henry Emeleus]

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These layers generally exhibit strong lateral continuity, and the rhythmic layering can persist vertically through several metres of stratigraphy. At most localities the layering remains broadly conformable with the surrounding major lithological units or members. A preferred orientation - igneous lamination - of tabular or prismatic crystals is also common. While igneous lamination typically aligns with the small-scale layering, exceptions do occur.

Deviations from regular layering are abundant and often resemble sedimentary structures found in fluvial or marine sandstone deposits. These include lateral variations in layer thickness, cross-stratification, graded bedding, and slump features. Graded layering is most frequently observed in the bytownite-troctolites (Figure 9-242). Here, grading reflects changes in mineral density rather than grain size - denser olivine tends to concentrate at the base of a layer, whereas plagioclase becomes progressively dominant towards the top. Such grading, as well as cross-stratification, suggests localized current activity within the magma. These features likely record episodic, vigorous magmatic circulation, possibly including localised turbidity currents. A particularly striking example is found in the Long Loch Member of the Central Intrusion, west of Long Loch, where a graded layer contains abundant rounded peridotite clasts that decrease in size upwards over *ca*. 1 m, from 10 cm to <1 cm in diameter. This layer, overlying bytownite-troctolite, has a scalloped and irregular basal contact with upward-projecting flame-like structures.



Figure 9-242: Graded layering due to modal mineral variation, Central Intrusion, NW of Long Loch. Compass *ca*. 10 cm long.

Some of the most remarkable sedimentary-like features in the Rum ultrabasic rocks are related to gravitational instability of the crystal cumulates, which resulted in downslope sliding and slumping. These deformed zones are commonly associated with relatively steep layering angles (>15–20°), suggesting either deposition on an overly steep slope or tilting prior to complete cumulate solidification. Other possible triggers include strong magmatic currents or seismic activity associated with the subvolcanic

magma chamber. The resulting slump structures (Figure 9-243; Figure 9-244) include convolute bedding, disorganized slump folds, slump breccias (indicating break-up of already consolidated material), irregular dips, and discontinuous layering (Wadsworth 1992). Such features are widespread in the bytownite-troctolites of the Eastern Layered and Central intrusions.



Figure 9-243: Slumps with deformation of load casts in Unit 14, Eastern Layered Intrusion, east face of Askival. Knife *ca.* 10 cm long.



Figure 9-244: Slumps with deformation of load casts in Unit 14, Eastern Layered Intrusion, east face of Askival. Knife *ca.* 10 cm long. [Photograph courtesy of David Brown]

Bowerbird

Although individual slump horizons are typically less than 2 m thick - implying a relatively thin layer of unconsolidated crystal mush - some exceptional examples occur. For instance, in Unit 15 on Askival summit, the ELI exhibits up to 30 m of contorted layering within bytownite-troctolite. Additionally, in Unit 13 on the SE flank of Hallival, thick slumped intervals involve both peridotite and bytownite-troctolite. These localities provide strong evidence for the presence of extensive, poorly consolidated cumulate deposits. Elias (1989) proposed that cumulates near the intrusion margins were mechanically unstable, that large volumes of unconsolidated material were transported by mass flow into central parts of the complex, and identified four major mass-flow depositional episodes in the bytownite-troctolite and peridotite of the upper part of Unit 12 on Hallival.

9.9.9.2 Harrisitic Peridotite and Bytownite-Gabbro

Harrisitic peridotite and bytownite-gabbro are among the most distinctive components of the Rum Layered Suite. Harrisite layers are generally integral, non-transgressive features within the layered sequence, rather than late-stage pegmatitic intrusions (though see Donaldson 1982). They are most prominently developed in the WI, where they constitute a significant portion of the succession between Harris Bay and the summit of Ard Mheall, but are less common elsewhere in the Layered Suite.

The hallmark of harrisitic texture is the presence of elongate olivine crystals exhibiting branching or skeletal (parallel growth) habits, typically oriented at high angles to the layering (Figure 9-245; Figure 9-246; Figure 9-247). This texture is accentuated by interstitial feldspar and, to a lesser extent, clinopyroxene. The upper surfaces of harrisitic layers are commonly irregular due to variable crystal growth rates and are always marked by a sharp decrease in crystal size. These layers range in thickness from a few centimetres to over a metre, and individual layers tend to be texturally uniform. In some cases, layers contain moderately large olivines in a more random orientation - features commonly found in the lower, marginal parts of the Harris Bay Member.



Figure 9-245: Elongate, skeletal olivine crystals (*ca.* 1 m long) WLI. [Photograph courtesy of Valentin Troll]

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Figure 9-246: Elongate, skeletal olivine crystals (*ca.* 1 m long), Western Layered Intrusion. [Photograph courtesy of Valentin Troll]

Initially described by Harker as 'pegmatoid', harrisites were later interpreted by Wager & Brown (1951) and Wadsworth (1961) as the result of upward crystal growth at the magma-cumulate interface during periods of non-deposition of cumulus crystals. Donaldson (1974, 1976) further investigated these olivines and concluded that the harrisitic texture forms through rapid crystal growth under conditions of extreme supersaturation, most likely induced by slow cooling.

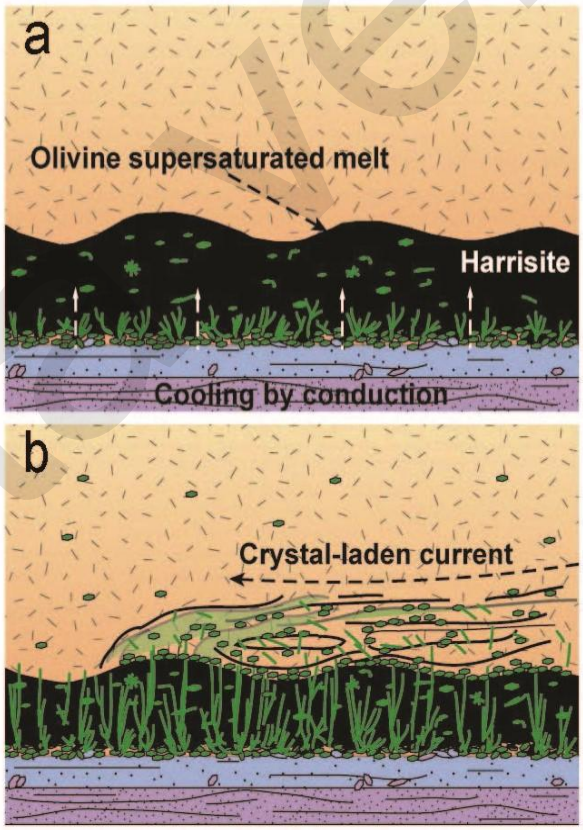


Figure 9-247: Successive stages in the formation of harrisitic structures (after O'Driscoll *et al.* 2007). Harrisitic olivine growth (a) is repeatedly interrupted by replenishments to produce both *in situ* and broken varieties (b). [Figure courtesy of Valentin Troll]

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9.9.9.3 Poikilomacrospherulitic feldspars

A similarly striking, though rarer, feature described by Donaldson *et al.* (1973) involves radiating, bifurcating plagioclase rays - up to 40 cm long - enclosing numerous small olivine crystals (Figure 9-248; Figure 9-249). These so-called 'poikilomacrospherulitic' feldspars occur in the Dornabac Member of the Central Intrusion, particularly on a shelf east of Loch an Dornabac. These structures most likely crystallised *in situ* from a more hydrous, feldspathic magma.



Figure 9-248: Poikilomacrospherulitic feldspars of the so-called 'starfish rock' in the Dornabac Member of the Central Intrusion, east of Loch an Dornabac. Compass *ca.* 10 cm long.



Figure 9-249: Poikilomacrospherulitic feldspars of so-called 'starfish rock' in the Dornabac Member of the Central Intrusion, east of Loch an Dornabac. Compass *ca.*10 cm long. [Photograph courtesy of David Brown]

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9.9.9.4 Replacement structures

Small-scale replacement of bytownite-troctolite by peridotite is relatively common in the Rum ultrabasic rocks. Features attributed to this process include 'upward-growing pyroxene structures' (Brown 1956), now more widely known as finger structures (Robbins 1982; Butcher *et al.* 1985), as well as late-stage vein networks (Butcher 1985). Finger structures are widespread and consist of narrow, elongate dunitic or feldspathic peridotite bodies, typically 2–3 cm in diameter, which extend vertically from peridotitic units into overlying bytownite-troctolite for several to tens of centimetres (Figure 9-250). These features are composed of cumulus olivine and plagioclase cemented by poikilitic, upward-tapering crystals of clinopyroxene. Notably, they commonly penetrate undisturbed layering, igneous lamination, and slump structures in the overlying units.



Figure 9-250: Peridotite fingers penetrating undisturbed, overlying layered troctolite, Central Intrusion, east of Minishal. Hammer shaft *ca.* 30 cm. [Photograph courtesy of Valentin Troll]

Butcher *et al.* (1985) interpret them as post-depositional replacement features formed by the upward migration of intercumulus melt, expelled during compaction of underlying peridotite, into more feldspathic overlying rocks. Alternatively, Morse *et al.* (1987) suggest they could form at the upper surface of mafic sills intruded into nearly solid bytownite-troctolite.

Larger-scale, less-regular replacement features are also observed, particularly in higher units of the ELI (Bedard *et al.* 1988). For example, on the northern shoulder of Hallival, remnants of the classic 'anorthositic bytownite-troctolite – chromitite - feldspathic peridotite' sequence at the Unit 11/12 boundary (Brown 1956) now occur as isolated patches within peridotite that has replaced significant

portions of Unit 11. In such cases, chromitite layers can survive as relicts within the replacement peridotite (Butcher *et al.* 1985; Emeleus 1997).

Near to the top of Unit 9, on a shelf *ca.* 700 m due north of the summit of Hallival, a wavy, irregular contact exists between bytownite-troctolite and overlying dark, clinopyroxene-rich bytownite-gabbro. This boundary is discordant to igneous lamination, anorthosite schlieren, and coarse-grained layers, some of which cross the contact. Pipe-like intrusions of bytownite-troctolite extend into the overlying rock, which also contains isolated, rounded inclusions of troctolite (Brown 1956; Young & Donaldson 1985; Bédard *et al.* 1988; Elias 1992). Young & Donaldson (1985) interpreted these undulations as forming spontaneously at the interface between two fluids with an inverse density gradient. Similar structures in Unit 14 on Trallval have been described by Volker & Upton (1990) as flame structures resulting from gravitational loading. If these are indeed loading structures, it implies that igneous lamination and textural layering formed later, during post-cumulus recrystallisation (cf. Irvine 1980; Hunter 1987). An alternative explanation is that the pyroxene-rich bytownite-gabbro formed by metasomatic alteration of troctolite infiltrated by basaltic melt (Bédard *et al.* 1988; Bedard & Sparks 1991; Elias 1992; but see Volker & Upton 1992 for a critique).

However, an assessment of the degree of textural equilibrium in a traverse across the Unit 9 feldspathic peridotite supports this intrusive relationship interpretation: the troctolites above (i.e. the 'Unit 9 troctolite') and below (i.e. the 'Unit 8 troctolite') preserve evidence of a considerable variability in the degree of textural equilibrium, possibly caused by the intrusion of the feldspathic peridotite, essentially a sill (i.e. the 'Unit 9 feldspathic peridotite') (Holness *et al.* 2007). Elsewhere in the ELI, uniformly equilibrated textures infer that other feldspathic peridotites have a non-intrusive relationship to the troctolites and that the wholesale intrusive interpretation for the feldspathic peridotites by Bédard *et al.* (1988) is flawed. Movement of interstitial melt within the crystal pile, referred to as 'infiltration metasomatism' by Holness *et al.* (2012), can also be inferred from the textural characteristics of the Rum cumulates.

Within Unit 9 of the ELS, a conspicuous pyroxene-rich gabbro layer has an undulating 'wavy' base against the subjacent troctolite and is referred to as the Wavy Horizon (Figure 9-251; Figure 9-252; Figure 9-253). Classically, the nature of this boundary has been likened to load casts and flame structures in clastic sedimentary rocks that have undergone soft-sediment deformation (see Emeleus 1997). Similar features have been reported from elsewhere within the ELI (Emeleus & Troll 2014). Bédard *et al.* (1988) suggested that such boundaries form by some form of replacement process and Holness *et al.* (2007) concluded from textural characteristics of material from across the Wavy Horizon that some form of metasomatic process involving ascending late-stage melts derived from the subjacent crystallising peridotite, resulted in the extensive clinopyroxene crystallisation within the Wavy Horizon (and other similar interfaces within the ELI, WLI and CI). A major implication of such an interpretation is that, potentially, migrating residual (or 'late-stage') melts have modified or even overprinted original magmatic features. From a detailed textural and geochemical study of the troctolite of Unit 12 of the ELI, Holness & Winpenny (2009) concluded that it accumulated from up to seven pulses of (picritic to basaltic) magma within a sill-like chamber that may have been only a few tens of metres thick.

Beta version



Figure 9-251: The Wavy Horizon within Unit 9 on the north of Hallival, separating layered troctolite from overlying dark, pyroxene-rich gabbro, ELI. Hammer *ca*. 30 cm long. [Photograph courtesy of Valentin Troll]



Figure 9-252: The Wavy Horizon within Unit 9 on the north of Hallival, separating layered troctolite from overlying dark, pyroxene-rich gabbro, ELI. Knife *ca*. 8 cm long. [Photograph courtesy of David Brown]



Figure 9-253: The Wavy Horizon within Unit 9 on the north of Hallival, separating layered troctolite from overlying dark, pyroxene-rich gabbro, ELI. Pole *ca*. 1 m long.

9.9.9.5 Intrusive versus cumulative origins of peridotite

The peridotites of the Eastern Layered Intrusion were traditionally considered integral parts of the cumulate sequence (Brown 1956; Wager & Brown 1968). However, it is now recognized that many peridotite bodies are intrusive. For example, peridotite and rare dunite plugs cut the layered rocks, and peridotite previously mapped as the base of Unit 9 on the northern slopes of Hallival intrudes parts of Units 9 and 10 (see above; Bedard *et al*. 1988). Thin apophyses and tongues of peridotite also intrude bytownite-troctolite near to the top of Unit 14 (Renner & Palacz 1987), although in some cases, the relationships could be explained by slumping and disruption of originally layered peridotite.

Bedard *et al*. (1988) suggested that many thick peridotite bodies in the Eastern Layered Intrusion are intrusive sheets rather than members of the cumulate sequence (see above). Conversely, Volker & Upton (1990, 1991) argue that most of the conformable peridotite layers in the Trallval succession are depositional, not intrusive. However, they acknowledge the presence of intrusive peridotites, which they interpret as crystal mushes that were squeezed into surrounding rocks during periods of compression. Elias (1992) concluded that some features interpreted as intrusions may in fact result from mass-flow disruption of previously layered peridotite (see above).

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9.9.9.6 Mush processes, microstructures, textural equilibrium and porosity closure

Traditionally viewed as a static magma chamber formed through crystal settling from a single, cooling magma body (Brown 1956), subsequent investigations demonstrate that the Rum Central Complex is in fact the product of an open-system, multi-phase intrusion, shaped by complex interactions between melt and an evolving crystal mush (Holness 2005; Holness *et al.* 2007; Holness & Winpenny 2008). Detailed petrographic and microstructural analyses, including the quantification of grain boundary geometries, dihedral angles, and porosity distributions, indicate that the textures of Rum's cumulate rocks record not only the conditions of initial crystallisation, but also extensive post-cumulus processes such as compaction, melt percolation, and textural equilibration. Repeated remobilisation and recrystallisation of partially solidified mush in response to replenishing magma pulses, were capable of deforming or thermally overprinting earlier formed cumulates. These findings have led to a reinterpretation of Rum's iconic cyclic units, not as simple records of periodic crystal settling, but as 'archives' of episodic magma recharge, crystal mush remobilisation, and dynamic chamber evolution. These insights have reframed the intrusion as a time-integrated system of mush processes, melt extraction, and melt-rock interaction.

9.9.9.7 Veining in the Layered Suite

Thin ultrabasic and basic veins are a common feature within the layered ultrabasic rocks. Typically, 2-3 cm thick, though locally reaching up to 30 cm, these veins are generally concordant with the host layering, but may rarely be transgressive (Butcher 1985). They are commonly pyroxene-rich and gabbroic in composition.

Butcher (1985), based on studies of veins in Unit 10 of the ELI and parts of the WLI, concluded that these features formed through injection of late-stage liquids into fractures in crystallising cumulates. Reaction between these migrating liquids and the surrounding cumulus minerals caused extensive alteration within a halo of up to 1 cm on either side of the veins. For example, olivine adjacent to the veins shows a reduction in forsterite content from Fo_{84} to approximately Fo_{77}, whereas Ni and Mn contents remain unchanged - an alteration process Butcher (1985) termed channelled metasomatism.

A different category of veins and segregations was described by Kitchen (1985) in peridotite of the CI. Exposed for several hundred metres along the banks of the Kilmory River, south of Salisbury's Dam, these consist of irregular segregations and veins of pale grey teschenite, ranging from a few millimetres to 12 cm in width and up to 30 cm in diameter, with rare associated dykes. The teschenite contains coarse olivine ($Fo_{70–74}$), calcium-rich clinopyroxene, and plagioclase (An-rich cores, zoned to more sodic rims), along with kaersutite, phlogopite, ilmenite, magnetite, and apatite. Interstitial analcime forms 10–15 vol% of the rock and encloses a variety of minerals including euhedral actinolite, albite, titanite, zircon, skeletal arfvedsonite, apatite, epidote, and spherulitic chlorite. The presence of these veins suggests that crystallisation of Rum peridotites can produce alkali-rich, undersaturated residual liquids.

9.9.9.8 Ultrabasic breccias

Ultrabasic breccias are a distinctive feature of the Central Intrusion but are less common elsewhere in the Layered Suite. They occur along the contact between the Central and Western Layered intrusions, especially from the Abhainn Rangail, northwards. Breccias are less prevalent along the eastern margin. Within the CI, itself, linear breccia zones are prominent and appear to radiate from multiple centres near Ruinsival (Volker & Upton 1990).

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These breccias are composed of blocks of peridotite, feldspathic peridotite, or bytownite-troctolite (in places all three), set within matrices of feldspathic peridotite, bytownite-troctolite, or, less commonly, peridotite. Near the intrusion margins, breccias incorporate blocks derived from the adjacent Western or Eastern Layered intrusions; elsewhere, blocks originate from units within the Central Intrusion. The clasts vary from angular to rounded or subrounded, and some show evidence of ductile deformation. They may be either densely packed or dispersed within featureless or streaky matrices, and banding, where present, is commonly contorted around the clasts. Clast sizes range from a few centimetres to several metres, including blocks of well-layered cumulate rock (Figure 9-254; Figure 9-255).



Figure 9-254: Breccia, comprising fragments of peridotite of a wide range of shapes in a troctolite matrix. Pole *ca*. 1 m long.



Figure 9-255: Detail of breccia, comprising fragments of peridotite of a wide range of shapes in a troctolite matrix. Compass *ca*. 10 cm long.

To the SE of Long Loch, numerous exposures suggest that flowing feldspathic peridotite entrained large blocks during emplacement. For example, disoriented blocks of bytownite-troctolite and peridotite are enclosed in streaky feldspathic peridotite, while nearby, layered units divide around a large peridotite block (Figure 9-256; Figure 9-257; Figure 9-258; Figure 9-259).



Figure 9-256: Breccia of layered troctolite blocks in a feldspathic peridotite matrix (debris avalanche type), Central Intrusion, Harris track /Loch an Dornabac. Henry Emeleus for scale. [Photograph courtesy of Valentin Troll]

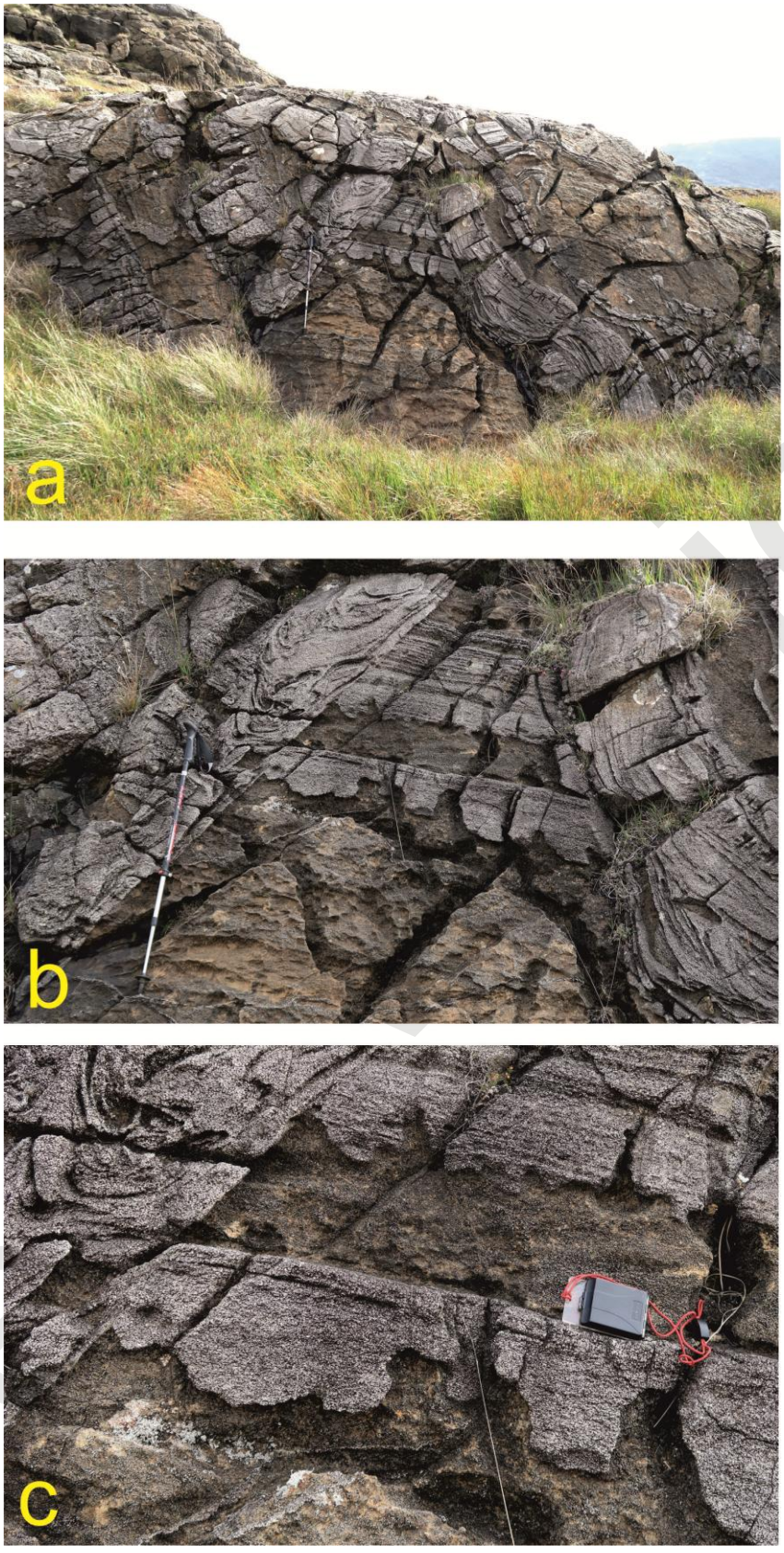


Figure 9-257: Large blocks of layered bytownite-troctolite and peridotite (note finger structures at internal contacts), with slumped and brecciated bytownite-troctolite draped over the top. The sense of movement is from top left to bottom right. Central Intrusion, *ca*. 120 m SSE of the southern end of the Long Loch. Pole *ca*. 1 m long.

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Figure 9-258: Disrupted (slumped and brecciated) material within the Central Intrusion. Pole *ca.* 1 m long. [Photograph courtesy of David Brown]



Figure 9-259: Disrupted (slumped and brecciated) material within the Central Intrusion. Pole *ca.* 1 m long.

Wadsworth (1961) initially interpreted the breccias as scree-like deposits formed at fault scarps within a magma chamber. Later work, including Donaldson (1975) and McClurg (1982), suggests that fragmentation occurred during intrusion of feldspathic peridotite magma into consolidated peridotite. Volker (1983) and Volker & Upton (1990) also support this model. Wadsworth (1992) re-mapped breccias

in the Long Loch - Loch an Dornabac area, concluding that these are intraformational debris deposits, possibly formed by sub-magmatic faulting within a central graben. These interpretations align with the hypothesis that the breccias formed during graben development accompanying the emplacement of the Central Intrusion. In this model, cumulate rocks collapsed and avalanched down fault scarps, while crystal- and clast-laden magma was simultaneously injected into fissures and between blocks (McClurg 1982; Volker 1983; Wadsworth 1992; see below).

9.9.10 Other peridotites in the Rum Central Complex

9.9.10.1 Peridotite tongues

Three N-S-trending tongues of peridotite intrude the Northern Marginal Zone (NMZ) between Long Loch and Loch Bealach Mhic Néill (Figure 9-260; Figure 9-261). The easternmost tongue forms a prominent ridge of brown-weathering peridotite and crosscuts the Main Ring Fault. The western tongue is truncated by Central Intrusion breccia SE of Long Loch. While no clear contacts have been observed, field relationships suggest all three tongues predate the Eastern Layered Intrusion, as layering in adjacent bytownite-troctolite crosses their strike.



Figure 9-260: Orange-weathered peridotite tongue west of Loch Bealach Mhic Nèill, NW of Barkeval, Rum. In the distance are pale-weathered ignimbrites forming Meall Breac.

Peridotite in these tongues commonly displays steep to vertical, N-S-oriented banding, contrasting with the shallow dips of layering in the surrounding troctolites. They consist primarily of peridotite and, to a lesser extent, feldspathic peridotite. While olivine content remains relatively constant, textural layering reflects variations in interstitial plagioclase and pyroxene, features described by Dunham (1965) as ‘matrix banding’.

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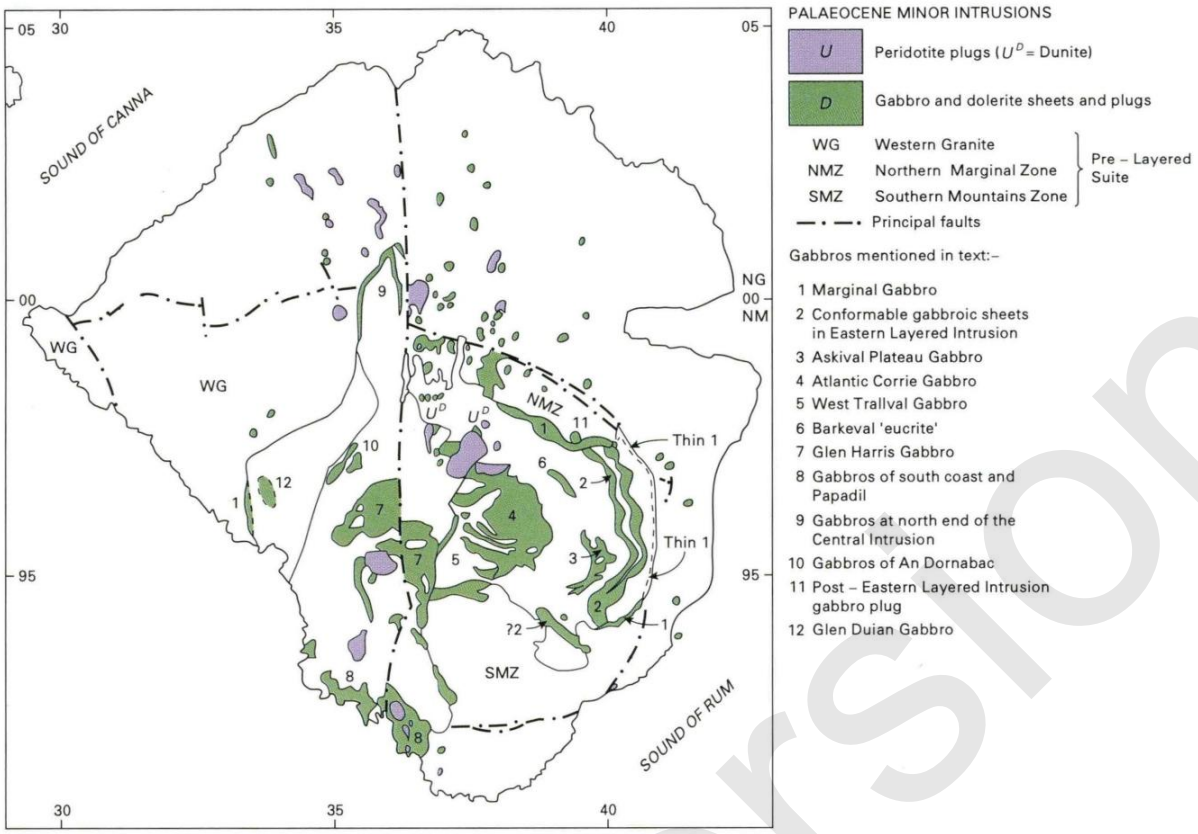


Figure 9-261: Distribution of gabbro sheets and plugs, and peridotite plugs in the Rum Central Complex and the surrounding rocks (after Emeleus 1997).

Additionally, several peridotite plugs intrude rocks of both the Eastern Layered and Central intrusions near Barkeval (Figure 9-261). The largest of these forms the summit of Barkeval and its steep SW slopes. A N-S-elongated dunite plug, located *ca.* 500 m SE of Long Loch, cuts through Central Intrusion breccias and a gabbro plug emplaced into the Eastern Layered Intrusion. The gabbro is notably altered and appears dull black due to thermal metamorphism caused by the intrusive peridotite (mineralogically, in places, a dunite).

9.9.10.2 Petrography and mineralogy

The general petrological framework of the Rum Layered Suite is marked by a distinctive cyclicity in large-scale (unit) layering, which is superimposed by finer-scale rhythmic layering (cf. Irvine 1987). Both petrological and geochemical characteristics of individual units are primarily controlled by their cumulus mineral assemblages.

9.9.10.3 Peridotites

Peridotites are dominated by cumulus olivine, with ubiquitous chromite, which is commonly locally concentrated into thin laminae (Figure 9-261; Figure 9-262; Figure 9-263). Augite and plagioclase occur as large ('poikilitic') inter-cumulus crystals, enclosing olivine and chromite. In more feldspathic peridotites, euhedral plagioclase may occur as an incipient cumulus phase. Textural variation in olivine-rich cumulates largely reflects changes in olivine crystal ('grain') shape and the proportion of interstitial pyroxene and plagioclase. Non-harrisitic peridotites (see below) display a range of textures from small equigranular olivine crystals with random orientation, to larger tabular crystals laminated parallel to the

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layering. Strain-induced twinning is common in olivine. These peridotites typically represent extreme adcumulates and show a high degree of textural equilibration (Hunter 1987), suggesting that primary compositional zoning, particularly in feldspar, was erased during high temperature recrystallisation.

9.9.10.4 Harrisitic rocks

Harrisitic rocks are texturally distinct and typically more feldspathic than normal cumulate layers. Pyroxene is uniformly sparse, except in the gabbroic Harris Bay Member of the WLI. Minor brown amphibole and biotite are present, along with alteration minerals such as chlorite, sericite, and colourless amphibole, reflecting higher interstitial liquid contents during crystallisation. Feldspar and pyroxene show minimal zoning, and olivine is unzoned. Donaldson (1974) interpreted the common occurrence of skeletal and dendritic olivine due to rapid crystal growth from slowly cooled, olivine-supersaturated magma. He later proposed (Donaldson 1982) that some harrisitic textures formed through rapid crystallisation of interstitial melt trapped beneath impermeable barriers. The branching of layers at Harris may indicate injection of migrating melt as a possible mechanism of formation for these rocks.

9.9.10.5 Bytownite-Troctolites and gabbros

Bytownite-troctolites show a broader modal variability, grading into bytownite-gabbros with increasing pyroxene. Plagioclase is the dominant cumulus mineral, although olivine and augite can be locally abundant. Chromite is scarce or absent. Most are adcumulates, though mesocumulates occur in Units 1–6 of the Eastern Layered Intrusion. Laminated textures are common, with feldspar laths typically aligned parallel to layering. The number and proportion of cumulus phases control textural characteristics. Cumulus plagioclase and olivine are commonly 'cemented' by overgrowths, rimmed feldspar, and poikilitic augite. Where augite is also cumulus, the overall cumulate texture becomes less distinct. Strongly laminated plagioclase adcumulates ('anorthosites') may contain poikilitic augite and olivine. Their uniform texture and mineralogy suggest significant post-cumulus re-equilibration (Hunter 1987). Supporting evidence includes small, randomly oriented feldspars enclosed by poikilitic pyroxene, around which lamination develops. Olivine commonly contains aligned, thin (*ca.* 1 μm) plates of magnetite and brown chrome-spinel, many dendritic.

9.9.10.6 Accessory and late-stage phases

Uranium-bearing minerals, such as zirconolite and baddeleyite, have been identified in intercumulus pockets (Henderson *et al.* 1971; Williams 1978). Late-stage sulphides are also present. Dunham & Wilkinson (1985) document a wide sulphide suite - including pyrrhotite, pentlandite, cubanite, bornite, chalcocite, chalcopyrite, troilite, native copper, and electrum (46.4% Au, 49.9% Ag) - in and above the Unit 11/12 chromitite of the Eastern Layered Intrusion. Sulphides also occur lower in the succession, near Allt nam Bà (Faithfull 1986), with elevated levels of gold and PGE, especially in Unit 1.

9.9.10.7 Hydrothermal alteration

General mineralogical characteristics (see above) and oxygen isotope data indicate interaction with circulating heated meteoric water throughout the Layered Suite, with alteration intensity greatest near the complex's margins. Despite this, pervasive hydrous alteration is limited. Nevertheless, most rocks contain fine-scale (1–5 μm) veins and patches of sericite, biotite, magnetite, amphibole, carbonate, and chlorite. Olivine is commonly altered to brown clay minerals along fractures and crystal boundaries.

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9.9.10.8 Chromite-rich laminae

Thin chromitite and chromite-rich laminae occur in peridotites and at contacts between peridotite and bytownite-troctolite, particularly at unit boundaries (Figure 9-262) (Brown 1956). These seams, although typically <15 mm thick, can extend (intermittently) over 2 km (McClurg 1982). Chromite grains (<0.2 mm) are euhedral and deep brown to opaque, less commonly enclosing rounded inclusions of kaersutite, phlogopite, enstatite, apatite, and others (Volker 1983).

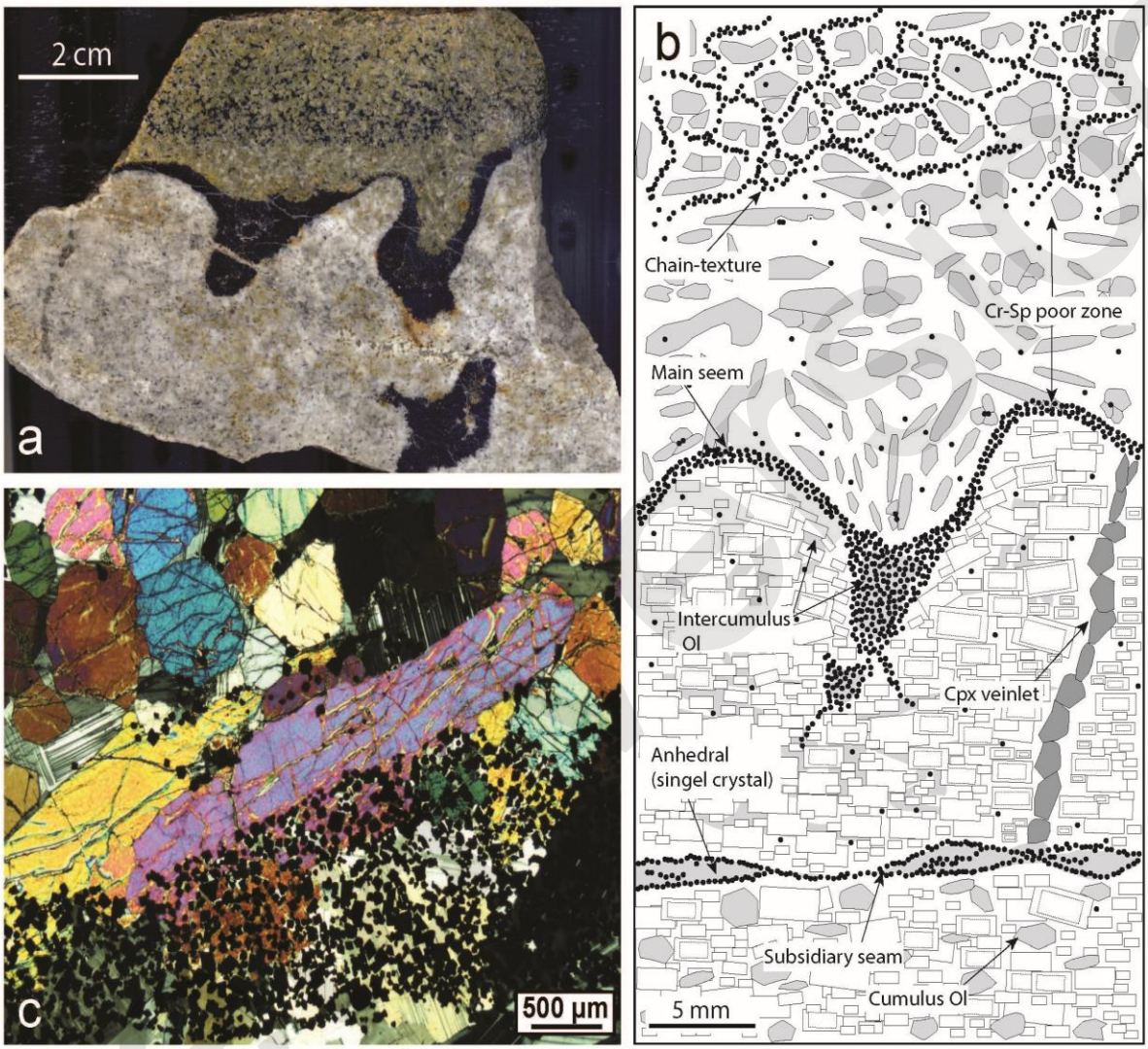


Figure 9-262: (a) Polished surface of downward-projecting chrome-spinel-rich cones developed on a chromitite seam (the Main Seam) at the contact of the Unit 8 peridotite with the underlying Unit 7 anorthositic troctolite. The cone structures transgress the flat-lying feldspar lamination in the troctolite and a package of chromitite appears to be detached from the right-hand cone, or, represents an elongation outside the area of view. Head wall of Coire Dubh; (b) A sketch of the relationships at the Unit 7/8 boundary shown in (a). A chrome-spinel-poor zone overlies the main seam and is in turn overlain by chrome-spinel-enriched peridotite. A subsidiary chromitite seam is underlain by laminated troctolite and separated from the overlying main seam by up to 20 cm of well laminated anorthositic troctolite that contains the detaching tip of a cone and is traversed by a near-vertical clinopyroxene veinlet; (c) Flat-lying, elongate cumulus olivine crystal apparently truncated at the Main Seam (crossed polarizers; crystal 4.5 mm long; after O'Driscoll *et al.* 2010). [Figure courtesy of Valentin Troll]

Whereas some structures suggest gravitational settling (e.g. rare geopetal structures; Volker 1983), the small crystal size implies *in situ* growth. Chromitite formation may have occurred at interfaces where picritic magma came into contact with feldspathic cumulates, leading to chromite precipitation. Chromitite rinds on irregular unit contacts, for example, where peridotite cuts the Unit 11/12 boundary NW of Hallival summit, support this. Volker (1983) also reports chromitite coatings on bytownite-troctolite and gabbro blocks enclosed by peridotite.

9.9.11 Mineral compositions, phase layering and cryptic layering

The minerals in the Rum Layered Suite exhibit remarkably narrow compositional ranges compared to other layered intrusions (cf. Wager & Brown 1968). Modal mineral variations in the Layered Suite are accompanied by subtle, systematic changes in mineral compositions, a phenomenon known as 'cryptic layering' (Wager & Deer 1939). The overall compositional trend from the base to the top of a unit reflects a transition from higher- to lower-temperature members of mineral solid-solution series. Olivine is the only cumulus phase consistently present throughout each unit. Therefore, the fundamental pattern of cryptic layering is best expressed through variations in forsterite/fayalite content, with other minerals providing corroborative evidence.

The cryptic compositional variation within several layered units is illustrated in Figure 9-263. Iron enrichment in olivine generally increases upward within a unit, although deviations from this trend do occur. Similar high- to low-temperature compositional ranges are observed in cumulus plagioclase and, less commonly, in pyroxene and chrome-spinel. Sharp breaks in compositional trends do not always coincide with unit boundaries; for example, the most magnesian olivines may be located a few metres above the base of a unit, and the most iron-rich olivines may occur below the top. Additionally, olivine compositions in some instances exhibit reversals within a unit, apparently linked to the thickness of olivine-rich layers (Faithfull, 1985; Figure 9-263).

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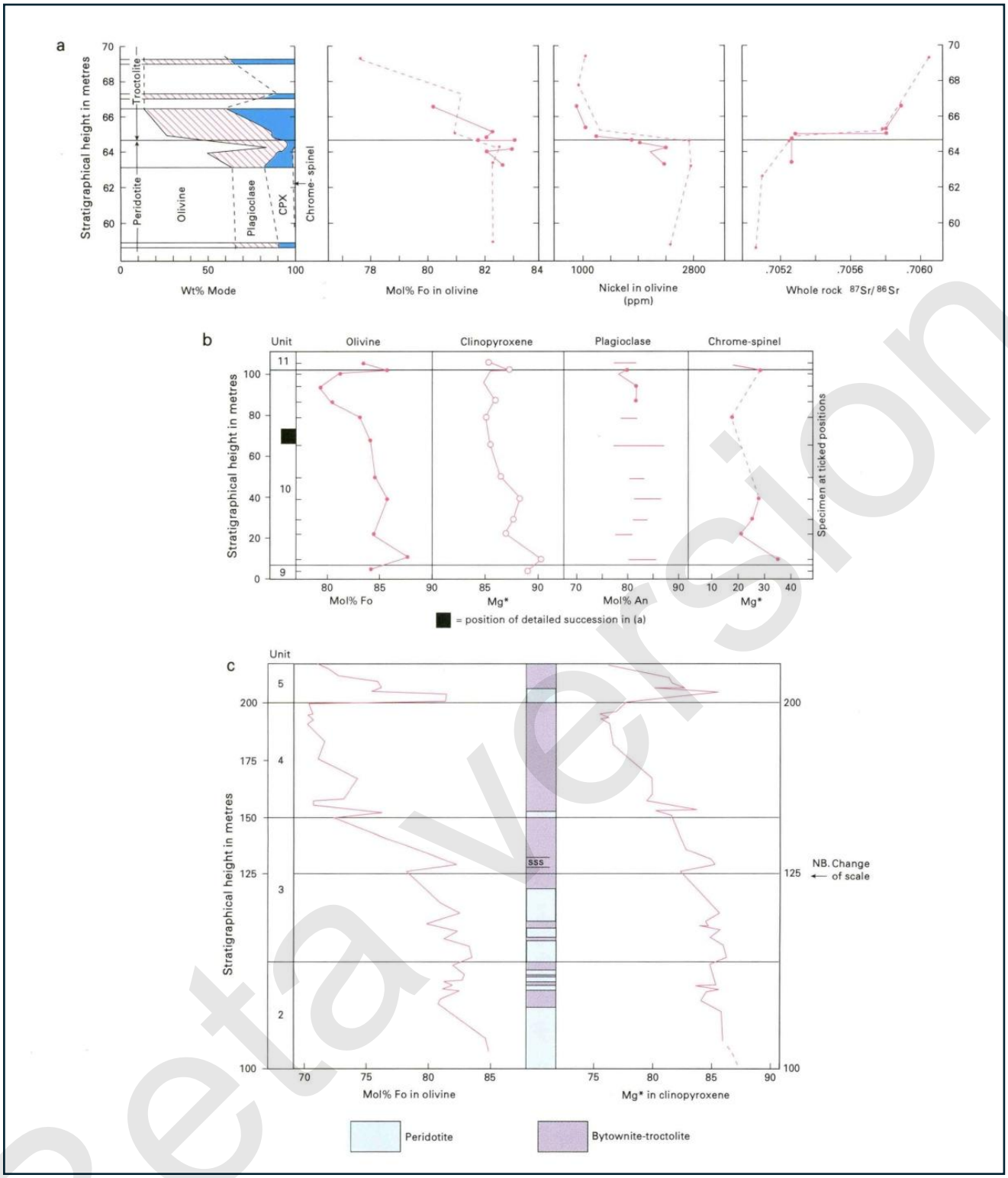


Figure 9-263: Cryptic variation in units of the Eastern Layered Intrusion: (a) variation in mode, olivine composition (Mg/Fe as % Fo, and Ni) and whole-rock $^{87}Sr/^{86}Sr$ across the main peridotite-bytownite-troctolite boundary within Unit 10 [dashed line with points] - from a series of closely spaced samples, [dashed line without points] from the main series of samples (after Tait 1985); (b) mineral compositional variation in Unit 10 and the adjoining units. • = cumulus minerals, o = intercumulus minerals, [solid line] = range of compositions of intercumulus plagioclase (after Dunham & Wadsworth 1978). The Mg number, Mg* = atom. % 100 Mg/ (Mg + Fe); and, (c) variation in olivine and pyroxene compositions in the lower units of the intrusion. sss = prominent slumping (after Faithfull 1985).

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Dunham & Wadsworth (1978) interpret the cyclic pattern of phase and cryptic layering as best explained by cumulate deposition from repeated influxes of fresh magma into a subvolcanic magma chamber, which is periodically emptied, or partially emptied, by volcanic eruptions. The cryptic variations within each unit thus record slight progressive fractionation as a batch of magma cools. Compositional reversals near to the top of each unit most likely result from some mixing between the residual magma of one unit and the initial pulse of fresh, undifferentiated magma entering the chamber. Alternatively, the variation pattern could arise when an influx of dense picritic magma establishes convection, displacing the residual, low-density evolved interstitial magma within underlying bytownite-troctolite cumulates (Tait 1985). In this scenario, cumulus minerals in the bytownite-troctolite would equilibrate with downward-percolating primitive liquid, yielding less evolved compositions and complementary effects in the basal part of the overlying peridotite. Elsewhere, compositional gradients adjacent to thin basic veins support the idea that olivine readily re-equilibrates (Butcher 1985).

Other cumulus phases with more limited stratigraphic ranges tend to mirror changes in olivine composition (Dunham & Wadsworth 1978; Faithfull 1985, 1986; Tait 1985). Notably, cumulus chromite shows significant variation in Mg/(Mg + Fe) ratios. However, interpreting chromite data requires caution to minimize the influence of late-stage reactions between chromite and surrounding minerals (cf. Henderson & Suddaby 1971; Henderson 1975; Henderson & Wood 1981).

Within Unit 10, compositional breaks are evident at the major boundary between peridotite and bytownite-troctolite (Figure 9-263), with similar breaks occurring elsewhere within other units. Whereas Mg-Fe variation in olivine is gradational, Ni displays a sharp break. This suggests that Ni may be less susceptible to alteration during olivine re-equilibration, thus preserving a 'memory' of the initially forsterite-rich olivine in the peridotite.

9.9.12 Geochemical characteristics of rocks in the Layered Suite

Unit 10 of the ELI was treated as the type layered unit by Brown (1956). Its elemental and isotopic compositions have been extensively studied by Tait (1985) and Tait & Palacz (1985), whose analyses represent peridotite, feldspathic peridotite, and bytownite-troctolite.

In the peridotite, high MgO (37.8%) and Ni (>1900 ppm) reflect the abundance of magnesian olivine, while high Cr (>6000 ppm) is hosted in discrete chromite, chromite inclusions within olivine, and clinopyroxene (Tait 1985). Low CaO (3.7%), Na_2O (0.24%), and Al_2O_3 (4.5%) correspond to the minor presence of plagioclase (Figure 9-263; Tait 1985). Incompatible element concentrations are very low, with rare-earth elements ranging from one to two times chondritic levels (Palacz & Tait 1985), and a slight positive Eu anomaly.

Differences between feldspathic peridotite and peridotite primarily arise from increased modal plagioclase rather than major changes in mineral compositions (Figure 9-263; Tait 1985; Palacz & Tait 1985). The mineral modes and compositions (Tait 1985) and bulk rock composition of the bytownite-troctolite differ markedly from those of the peridotites. Notably higher CaO (14.0%), Na_2O (1.74%), Al_2O_3 (16.8%), and Sr (228 ppm), result from the greater proportions of slightly more sodic plagioclase, whereas lower MgO (13.1%) and Ni (253 ppm) largely reflect a smaller modal amount of less forsteritic olivine.

A progressive decrease in Cr content upwards through Unit 10 corresponds to decreasing amounts of chromite. Incompatible elements are generally slightly more abundant in the bytownite-troctolite, with rare-earth elements approximately two to three times chondritic values, a pronounced positive Eu anomaly, and indications of light rare-earth enrichment.

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Compositional variations within rock types in this unit may partly reflect melt percolation from adjacent units. Dunitic peridotite near to the base of Unit 14 exhibits an extreme composition (MgO 40.0%, Al_2O_3 2.0%, CaO 1.23%, Cr 2515 ppm, Ni 1708 ppm) due to very high olivine content (87.6 vol.% of Fo_{85}; Renner & Palacz 1987), resembling an olivine adcumulate from Ard Mheall (Wadsworth 1961).

Volker (1983) analysed the matrices of ultrabasic breccias in the Central Intrusion and found their major and trace element compositions essentially similar to those of peridotites and bytownite-troctolites. They appear to be mixtures of varying proportions of olivine (Fo_{88}) and plagioclase (An_{84}). Differences between a harrisitic cumulate and an olivine adcumulate from the Ard Mheall Member of the Western Layered Intrusion (Wadsworth 1961) seem largely attributable to higher modal amounts of calcic plagioclase in the harrisitic rocks. Although amphibole, phlogopitic mica, and apatite are common in harrisitic rocks, which might suggest higher incompatible element contents, modern analyses are lacking. However, a segregation in harrisitic peridotite has a composition similar to feldspathic peridotite without clear evidence of incompatible element enrichment.

The chilled facies of the Eastern Layered Intrusion on Beinn nan Stac (Greenwood *et al.* 1990) corresponds to picritic basalt. Its slightly elevated K_2O (0.44%) and Rb (9 ppm) compared to the least evolved basalts on Rum may result from contamination by Torridonian feldspathic sandstone.

9.9.13 Radiogenic isotope characteristics of the Layered Suite

Radiogenic isotope studies in the upper part of the Eastern Layered Intrusion, from Unit 9 to Unit 15, have been carried out by Palacz (1984, 1985), Palacz & Tait (1985), and Renner & Palacz (1987). The variation in the $^{87}Sr/^{86}Sr$ ratio throughout this portion of the intrusion is summarised in Figure 9-264. Palacz (1985) notes that age corrections are largely insignificant, as rubidium (Rb) is typically excluded from the cumulate rocks. Additionally, Greenwood (1987) measured Sr and Pb isotope compositions in the marginal contact zones surrounding the Layered Suite.

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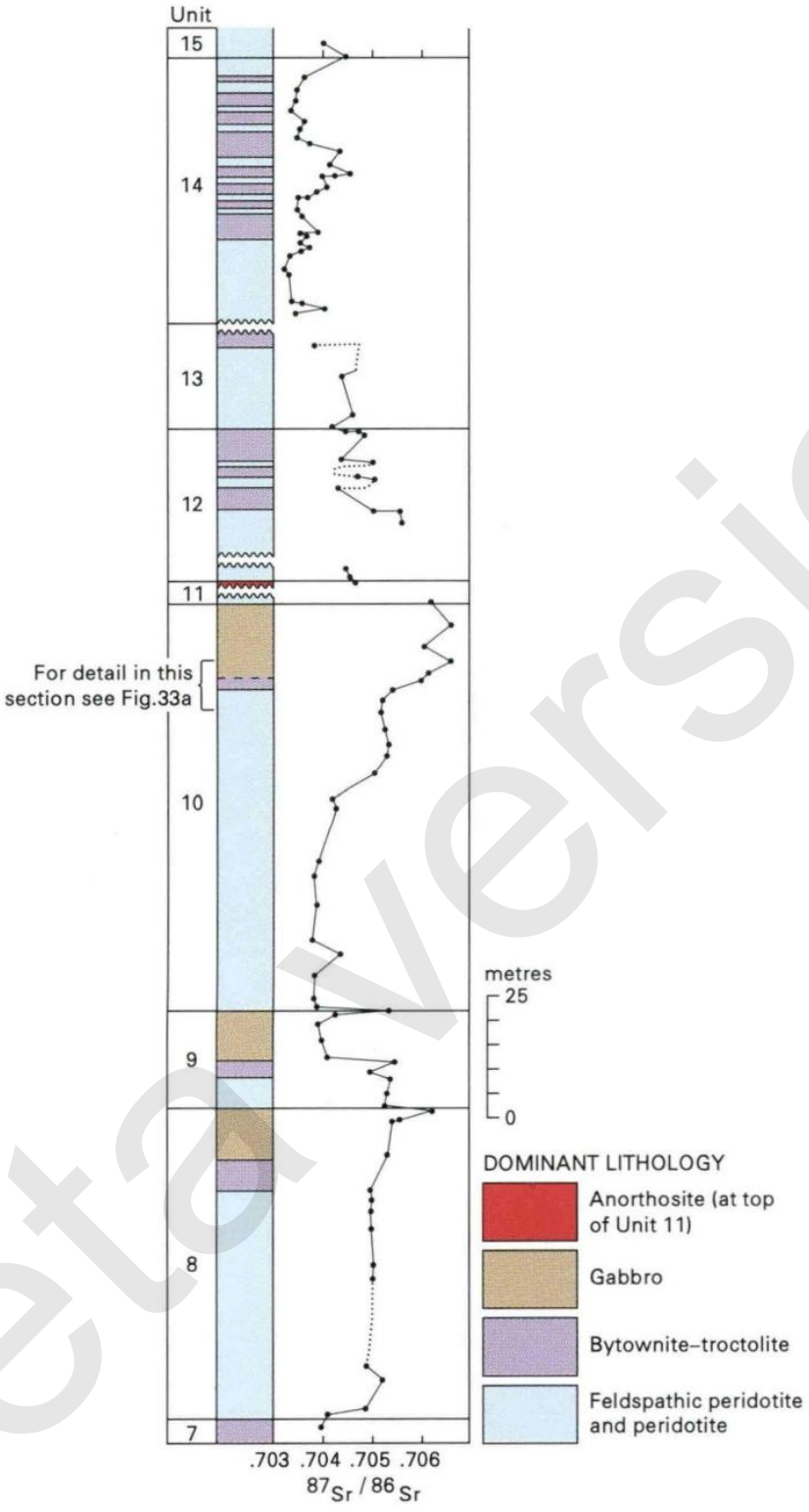


Figure 9-264: Variation in $^{87}Sr/^{86}Sr$ through the upper part of the Eastern Layered Intrusion, Hallival, Rum. Based on Palacz (1985, fig. 3), Palacz & Tait (1985, fig. 3) and Renner & Palacz (1987, fig. 2).

In Unit 10, the peridotite exhibits low $^{87}Sr/^{86}Sr$ ratios, ranging between 0.7036 and 0.7043. The corresponding $^{143}Nd/^{144}Nd$ ratio (at 60 Ma) is 0.51281. In contrast, the feldspathic peridotite shows significant isotopic variation up through the sequence: $^{87}Sr/^{86}Sr$ increases from 0.7049 to 0.7053, while $^{143}Nd/^{144}Nd$ decreases from 0.51271 to 0.51253. This trend becomes more pronounced in the bytownite-

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troctolite, where $^{87}Sr/^{86}Sr$ rises to approximately 0.706, and $^{143}Nd/^{144}Nd$ decreases further to between 0.51249 and 0.51238.

Unit 9 displays an unusual feature: its upper half consists of gabbro, marking an abrupt upward transition from bytownite-troctolite. This lithological change is accompanied by a notable shift in $^{87}Sr/^{86}Sr$, dropping from approximately 0.705 in the troctolite to a more uniform value of about 0.704 in the gabbro (Figure 9-264). The bytownite-troctolites within the Eastern Layered Intrusion are distinguished by relatively high radiogenic Sr content in comparison to the olivine-rich peridotites. This isotopic pattern, together with other geochemical evidence, supports the interpretation that the troctolites crystallised from magmas contaminated by basement Amphibolite Facies Lewisian gneiss (Chapter 2), whereas the magmas responsible for the peridotites were comparatively uncontaminated (Palacz 1985).

However, in Unit 14 on Hallival, much of the bytownite-troctolite exhibits low radiogenic Sr content (Figure 9-264), suggesting that pulses of uncontaminated basaltic magma were intermittently injected into the magma chamber (Renner & Palacz 1987). Lead isotope data determined by Palacz (1985) indicate minimal contamination from Torridonian sources (Chapter 2), although significant crustal contamination from Amphibolite Facies Lewisian gneisses is evident (Palacz 1985).

9.9.14 Gabbros in the Rum Layered Suite

9.9.14.1 Introduction

Gabbroic rocks occur throughout the Rum Layered Suite, including in the Eastern Layered Intrusion, the Central Intrusion, and the basal part of the Western Layered Intrusion (Figure 9-261). These gabbros include a variety of rock types: gabbro, olivine-gabbro, bytownite-(olivine)-gabbro (formerly termed ‘eucrite’), and, less commonly, quartz-gabbro. The numbered intrusions, indicated below, refer to the number of the intrusion in Figure 9-261.

9.9.14.2 Eastern Layered Intrusion gabbros

Marginal Gabbro (1)

Brown (1956) identified a zone of structureless gabbro along the northern and eastern margins of the Eastern Layered Intrusion. This zone varies in width from over 100 m to being locally absent, particularly west of Allt a’ Mhill Bhric. Due to the weathering of the mafic rocks, exposures are generally poor. The mineralogy is variable and includes augite, zoned plagioclase ($An_{77–51}$), and opaque oxides, with rare occurrences of quartz, orthopyroxene and olivine.

Greenwood (1987) studied the external contacts of the Layered Suite and observed that ultrabasic rocks crop out near to the country-rock Torridonian strata (Chapter 2) and the Western Granite (see above). Greenwood *et al*. (1990) document the presence of peridotite within mafic breccias, for instance at Upper Dibidil and north of Allt nam Bà, along with rare occurrences of chilled picritic rocks in contact with the country-rocks. Greenwood (1987) concluded that these marginal gabbros are not separate intrusions but rather result from the contamination of peridotite and bytownite-troctolite by siliceous crustal rocks. Isotopic data support this interpretation: Torridon Group feldspathic sandstones (Chapter 2), with high $^{87}Sr/^{86}Sr$ values (>0.757 at 60 Ma; Greenwood 1987), most likely underwent partial melting at temperatures around 960 ± 40°C, and the resulting melts interacted with basaltic magma during boundary flow. The final products crystallised as gabbros with elevated $^{87}Sr/^{86}Sr$ (*ca*. 0.705–0.707). Additionally, microgranodioritic rocks (with $^{87}Sr/^{86}Sr$ from 0.7107 to 0.7145) in the contact zone are thought to have formed by assimilation

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combined with fractional crystallisation. Oxygen isotope studies show extensive interaction between the marginal rocks and heated meteoric water (Greenwood 1987; Greenwood *et al.* 1992), which may explain the altered nature of these rocks.

Conformable Sheets (2)

Two sheets of fine-grained, pyroxene-rich bytownite-troctolite and troctolitic gabbro occur on the eastern slope of the Hallival-Askival ridge, near the stratigraphic levels of Units 4 and 5. North of Beinn nan Stac, the two sheets merge to form a unit *ca.* 110 m thick (Brown 1956). These rocks most likely extend into the thick bytownite-troctolite exposures in Upper Dibidil. Their distinctive purple-grey contrasts with the dull grey of typical bytownite-troctolite and the brown hues of peridotite. Chemically, they resemble the bytownite-troctolites in the layered succession.

These rocks are fine- to medium-grained, featuring patchy, wispy banding and common feldspar lamination (Faithfull 1986; cf. Brown 1956). Xenoliths of peridotite, bytownite-troctolite, gabbro, and beerbachite (a fine-grained, equigranular basic rock) are present in the lower sheet, particularly around Allt Mór na h-Uamha. The upper sheet also contains inclusions and makes intrusive contact with the overlying Unit 6 peridotite, incorporating numerous peridotite xenoliths. These feldspar-rich olivine gabbros and troctolites are texturally indistinct from layered bytownite-troctolites. They contain euhedral plagioclase ($An_{62–64}$), less commonly with calcic cores (An_{69}; Brown 1956), abundant pale brown augite, and common anhedral olivine (*ca*. Fo_{79}; Faithfull 1985). Harker (1908) and Brown (1956) considered these to be intrusive gabbros.

Askival Plateau Gabbro (3)

This unit consists of thin gabbroic sheets and veins, averaging 8 m thick, that cut across and disrupt layering in Unit 10 on a shelf east of Askival. The rock is characterised by granular, bent feldspars and abundant opaque oxides, indicating intrusion into a partially solidified host (Brown 1956). It may be genetically related to Unit 4.

Atlantic Corrie Gabbro (4)

The Atlantic Corrie Gabbro comprises a network of intrusive sheets that cut and brecciate the Eastern Layered Intrusion in Atlantic Corrie and on the northern side of Trallval (Volker & Upton 1990). This gabbro typically contains well-laminated plagioclase, with core compositions around An_{85}, zoning toward An_{61} and rarely down to An_{54} at the margins. In some cases, clinopyroxene is also laminated. Opaque oxides are rare. Subhedral olivine (Fo_{77} cores, Fo_{68} margins) is consistently present, and biotite occurs locally in significant amounts. The gabbro displays a subdued, undulatory banding, typically on a scale of 5 to 20 cm (Volker 1983).

9.9.14.3 Other gabbros

East Trallval Gabbro

This dyke-like intrusion is located at the eastern end of Trallval and cuts both the layered ultrabasic rocks and the Atlantic Corrie Gabbro (see above). The rock is pale, fine- to medium-grained, rich in plagioclase ($An_{55–44}$), and contains rare olivine (Fo_{65}). Biotite and opaque oxides are common.

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West Trallval Gabbro

Situated on the western end of Trallval, this gabbro forms a thin dyke, averaging 15 m in width and extending *ca*. 1 km in an NNE–SSW direction. It is a coarse-grained melagabbro, characterised by large ophitic clinopyroxene crystals up to 15 cm across and minor amounts of olivine. The dyke follows a fault that separates the Eastern and Central layered Intrusions (Volker 1983).

Barkeval 'Eucrite'

Several sheets of coarse-grained gabbro intrude layered rocks 300–1100 m NNW of Hallival summit. Brown (1956) identified calcic plagioclase ($An_{89–86}$ cores, zoned to An_{66} at rims) and termed these rocks the Barkeval 'eucrite' (bytownite-gabbro). He proposed they formed from interstitial liquid squeezed from nearby disturbed layered rocks. Another gabbro body intrudes the bytownite-troctolite of Unit 7 and the Unit 8 chromitite and peridotite in SE Coire Dubh, and contains zoned calcic plagioclase (cores $An_{80–69}$, rims $An_{64–69}$; Bédard *et al*. 1988).

Olivine Gabbro Plug

A small plug of fine-grained olivine gabbro cuts the contact between the layered intrusion and rhyodacite (ignimbrite) *ca*. 1.2 km north of Hallival. The rock is altered: sericitised labradorite laths are enclosed within ophitic clinopyroxene and altered anhedral olivine. Skeletal opaque oxides are partially overgrown by biotite, with secondary brown to green amphibole and chlorite replacing original mafic minerals.

Western Layered Intrusion

A marginal gabbro, similar to that found in the Eastern Layered Intrusion, occurs in multiple locations between the layered rocks and the older Western Granite (Wadsworth 1961) (see above). Along the eastern bank of the Glen Duian Burn, just upstream from the bridge, the Harris Bay Member of the WI is intruded by a set of thin (20–40 cm), slightly transgressive gabbro sheets referred to as the Glen Duian Gabbro (12, Figure 9-261) (Wadsworth 1961). These rocks are generally altered.

9.9.14.4 Central Intrusion

Glen Harris Gabbro (7)

This coarse-textured olivine-gabbro crops out along the floor of Glen Harris, extending south to Ruinsival and Leac a' Chaisteil. It has been offset dextrally by *ca*. 700 m along the Long Loch Fault (Figure 9-261). East of the fault, it forms a steep-sided boss, whereas to the west it forms flatter, possibly wedge-shaped bodies that intrude ultrabasic layered rocks and breccias (Volker 1983). The gabbro consists of zoned bytownite (An_{85} cores, An_{65} rims), discrete olivine crystals (Fo_{80}) moulded against plagioclase, poikilitic clinopyroxene, and magnetite. Originally referred to as the Glen Harris Eucrite (Wadsworth 1961), this body is thought to be downthrown 200-400 m west of the Long Loch Fault. Gabbro veins and sheets occur in sharp, though unchilled, contact with peridotite, which also appears as xenoliths -some hornfelsed, others plastically deformed.

Gabbros of An Dornabac (10)

At the northern end of the An Dornabac ridge, olivine-gabbro intrudes bytownite-troctolite of the Long Loch Member. The rock is dark and coarse-grained, containing streaky zones of feldspar-rich laminated rock and blocks of basic hornfels. Zoned labradorite ($An_{66–50}$) with rare bytownite cores is typically clouded. Olivine is uncommon. On the west side of the ridge, a dyke of bytownite-gabbro up to 100 m wide runs for *ca*. 1 km SSW from Loch an Dornabac, transgressing the layering of the Ard Mheall Member.

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Other gabbros

Olivine-bearing and olivine-free gabbro plugs and sheets (8, Figure 9-261) are widespread along the coast between Papadil and Rubha Sgorr an t-Snidhe, with smaller bodies located inland toward Ruinsival. These gabbros intrude Torridonian sandstones and, in some places, cut ultrabasic rocks. At Rubha na Pairce, however, peridotite intrudes the gabbro, enclosing rounded, thermally altered gabbro and dolerite xenoliths (Emeleus & Forster 1979). Similar altered gabbro occurs *ca*. 600 m NE of Loch Papadil.

At the northern edge of the Central Intrusion, gabbro (9, Figure 9-261) typically borders ultrabasic rocks. These gabbros are compositionally varied, ranging from bytownite-olivine-gabbro to more evolved, olivine-free types containing zoned plagioclase, orthopyroxene, biotite, and a quartz-alkali feldspar mesostasis. Several small, dyke-like gabbros also occur well within the Central Intrusion in this northern region.

A peridotite breccia containing angular gabbro blocks forms the SW shoulder of Trallval.

9.9.15 Intrusion breccias and thermal metamorphism

The Rum Layered Suite intrudes into country-rocks that are predominantly granitic or contain significant granitic components. The emplacement of hot basic (basaltic) and ultramafic (picritic) magmas has generated rheomorphic silicic melts, leading to the formation of intrusion breccias at these contacts (Figure 9-228; Figure 9-229) These breccias are present at all such interfaces and commonly exhibit the wholesale mobilization of country-rocks. For instance, at the Torridon Group margining gabbro on the coast SE of Loch Papadil, the original chilled margins of major mafic intrusions are rarely preserved; instead, they have been fragmented to form the bulk of the basic material in the breccias. This material typically appears as angular blocks lacking chilled edges. Less commonly, there is evidence of chilling on the edges of basic inclusions within silicic matrices, and these margins may display bulbous, crenelated forms characteristic of the co-mingling of contrasting magmas.

9.9.16 Contact zones and thermal alteration

9.9.16.1 Layered Suite and porphyritic rhyodacites

At Meall Breac, fine-grained olivine-gabbro intrudes rhyodacite. Approaching the contact with gabbro, basalt and feldspar-phyric basalt dykes within the rhyodacite are increasingly intersected by acid veins from the rhyodacite. The dykes do not cut the gabbro but protrude into it for over a metre, suggesting the removal of some rhyodacite by thermal erosion. At the contact, thin (*ca*. 2 cm wide) rhyolite veins are in sharp contact with angular fragments of basic rock, primarily fine-grained dolerites, and very rare peridotite blocks. These veins are similar to the rhyodacite but have a coarser groundmass and a lower modal proportion of phenocrysts. Sieve textures are common in plagioclase phenocrysts in the altered rocks. Within the gabbro, the veins become less distinct, adopting a granophyric texture and ultimately merging into a hybrid rock with plagioclase phenocrysts derived from the rhyodacite and feldspars from the gabbro. The gabbro adjoining these indistinct veins shows a gradual increase in micro-pegmatite towards the hybrids.

Similar intrusion breccias are present on Cnapan Breaca and in western Upper Dibidil, where breccia on slabs NE of Forgotten Corrie contains numerous peridotite fragments.

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9.9.16.2 Layered Suite and Western Granite

Exceptionally clear contacts between granophyre and bytownite-gabbro occur at the west end of Harris Bay and on the rocky headland to the SE (Figure 9-265). At the west end of the bay, bytownite-gabbro with flat-lying layers becomes fine-grained *ca*. 2 m from a 1–2 m wide zone of intrusion breccia, which separates the layered rocks from micro-granodiorite and quartz micro-diorite hybrids. The texturally variable silicic hybrids are characterised by acicular amphibole or chlorite, zoned plagioclase, and sieve-textured alkali feldspar in a matrix of delicate alkali feldspar-quartz intergrowths. The zone of hybrid rock is up to 15 m wide on the north side of a nearby cove. Between the Mausoleum and the cove, irregular, flat-lying sheets of silicic hybrid intrude the gabbro, and a complex zone of felsic box-veining and intrusive granitic pipes affects parts of the marginal gabbro. The contact between the Western Granite and silicic hybrids near the Mausoleum is sharp, but neither rock is chilled. The granophyre is a dull blue-grey rock with small (*ca*. 3 mm) areas of dark minerals, dull white feldspar, and rusty-weathering vugs up to 2 mm in diameter.



Figure 9-265: Sheets of harrisite invading the Western Granite, Harris Bay. [Photograph courtesy of David Brown]

One of the best-exposed intrusion breccia zones in the Hebridean Igneous Province crops out in low, wave-washed cliffs at the SE end of Harris Bay (Figure 9-266). Dull grey, thermally metamorphosed granophyre is intruded by thin (<1 m wide) basalt dykes, which are progressively veined and ultimately broken up in the rheomorphic silicic matrix, merging into a zone of intrusion breccia that margins the basic rocks. Feldspar phenocrysts in the altered granophyre range from normally-zoned plagioclase with

incipient sieve texture to indistinct alkali feldspar areas riddled with quartz. Fine-grained granular aggregates of amphibole, biotite, and opaques have replaced original pyroxene and amphibole. At this locality, there are instances where mafic inclusions have complicated chilled, rounded, crenelated margins against the silicic matrix.



Figure 9-266: Intrusion breccia at margin of the Layered Suite, SE end of Harris Bay, Rum.

9.9.16.3 Contacts Between the Layered Suite and Torridon Group Rocks

At a 50 m-high cliff near Loch Papadil, fine-grained sandstone of the Sgorr Mhòr Sandstone Member (Aultbea Formation, Torridon Group; Chapter 2) is in sharp, near-vertical contact with gabbro. The sandstone's originally horizontal layers tilt steeply (*ca.* 30° NW) close to the gabbro and eventually transition into an intrusion breccia made up of dolerite and, more rarely, gabbro blocks set in a fine-grained matrix of mobilized sandstone. Felsic veins within the nearby gabbro originated from partially melted sandstone (Figure 9-267).

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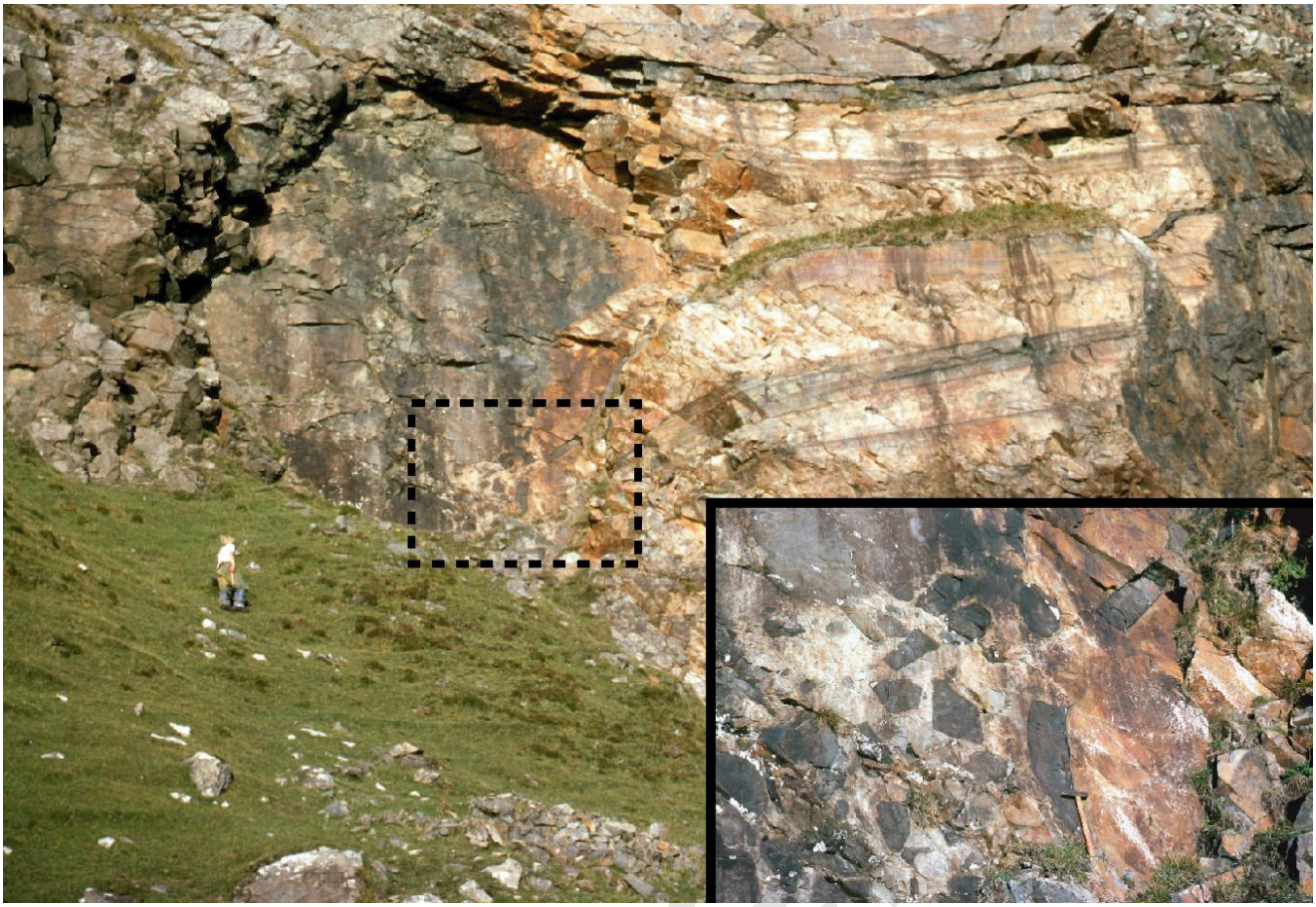


Figure 9-267: Gabbro of the Central Intrusion (dark rock above person) intruding bedded sandstone of the Sgorr Mhòr Sandstone Member (right-hand-side). SE of Loch Papadil. [Photograph courtesy of Valentin Troll]

A similar example occurs west of Inbhir Ghil, where recrystallized and partially melted sandstone is enclosed in gabbro. This rock contains tightly interlocked quartz grains, sanidine (i.e. high-temperature feldspar), and layers of heavy minerals now marked by magnetite crystals rimmed with fine biotite.

At Bealach an Fhuarain, gabbro intrudes both sandstone and several basalt cone-sheets. The resulting intrusion breccia contains basic rock fragments formed by the disintegration of both the basalt sheets and the gabbro margins.

South-SE of the ford at Allt na h-Uamha, over a distance of 250–600 m, gabbro and bytownite-troctolite intrude shale and siltstone. Intrusion breccia occurs on the west side of a nearby hill. The sedimentary rocks are significantly disrupted up to 30 m from the contact - lamination and fine bedding are bent and twisted - and basalt dykes are crosscut by thin silicic veins. These dykes ultimately break apart into elongated segments, separated by mobilized siltstone.

Differences in how various rock types respond to heat can be seen *ca.* 200 m west-SW, and *ca.* 400 m south-SE of the Allt Slugain a' Choilich hydroelectric dam. Shale breaks apart in a brittle manner, whereas adjacent sandy layers appear to flow between the shale fragments. This deformation is not due to soft-sediment behaviour, but rather indicates how arkosic sandstones are more easily mobilized during thermal metamorphism. Shaly and silty rocks have transformed into tough, siliceous hornfelses, commonly stained with iron. Coarser sandstones have become compact, pale grey rocks, locally with 'pustular' textures comprising small (2–5 mm) spherulites of intergrown quartz and alkali feldspar.

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9.9.16.4 Contacts between the Layered Suite and Lewisian Gneiss

Outcrops of the Lewisian Gneiss Complex (Chapter 2) commonly show clear signs of thermal metamorphism near contacts with the Layered Suite. Feldspar becomes dull and chalky white, while mafic minerals are green or dark grey. Partial melting is common. In places, such as Sandy Corrie, the NW slopes of Ainshval, and between Ard Mheall and Ard Nev, granitic material in intrusion breccias has formed by melting of granitic gneisses.

Early signs of gneiss alteration include iron oxide forming along hornblende cleavage planes and crystal edges. Pyroxene begins to form on the margins of hornblende and gradually replaces it entirely, along with the formation of opaque oxides. Plagioclase becomes cloudy and more calcium-rich with increasing metamorphism. Biotite, although rare, persists to high metamorphic grades, changing from dull brown to reddish orange. Coexisting pyroxenes in high-grade hornfelses indicate that the rocks were exposed to very high temperatures, *ca.* 1000°C (Dunham 1972; Greenwood 1987).

In pale (leucocratic) gneisses, intense heating has produced rims of intergrown quartz and alkali feldspar. In extreme cases, these rims form parallel-sided channels up to 2 mm wide. These textures most likely represent the initial stages of melt formation (rheomorphism). However, the original banding in the gneiss suggests that little melt was actually removed.

At the contact between the Western Granite and the Harris Bay Member of the Western Layered Intrusion, east of Harris Bay, elongated dark dykes are visible where they have been fragmented within a remobilized granitic matrix.

9.9.16.5 Contacts Between the Layered Suite and the Broadford Beds Formation (Lower Jurassic)

Near Allt nam Bà, gabbro from the Eastern Layered Intrusion cuts into and alters sandstones, shales, and limestones of the Lower Jurassic Broadford Beds Formation (Chapter 3). These rocks have been thermally metamorphosed and overprinted by deformation linked to movement on the Main Ring Fault. Rare calc-silicate xenoliths also occur nearby in the gabbro and the lower parts of the Eastern Layered Intrusion.

Pure limestone in the area has recrystallized into coarse, grey marble. Sandstones have hardened into quartzite. A magnetite-rich quartzite most likely represents a metamorphosed ironstone equivalent to rocks seen at Dibidil. Impure sandy limestones have transformed into a range of calc-silicate mineral assemblages.

A notable wall-like outcrop on the north bank of Allt nam Bà consists of pyroxene-rich, contaminated gabbro mixed with irregular talc-silicate patches. These are cut by thin syenite veins, which contain perthitic alkali feldspar (rimmed by albite), green aegirine-augite, and mica that may have replaced nepheline.

9.9.16.6 Inclusions of (possibly Palaeocene) basalt in the Layered Suite

Xenoliths of fine-grained, granular basalt, composed of olivine, plagioclase, clinopyroxene, magnetite, and rarely orthopyroxene, are common in the lower layers of bytownite-troctolite within the Eastern Layered Intrusion (Brown 1956; Faithfull 1986). These altered basalts, referred to as beerbachites by Richey & Thomas (1930), most likely come from the Paleocene Eigg Lava Formation (Chapter 6), which may originally have formed the roof of the Rum Central Complex.

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9.9.17 Oxygen Isotope Geochemistry of the Layered Suite

Studies of oxygen isotope ratios ($^{18}O/^{16}O$) in rocks from the Paleocene intrusive complexes of Skye, Mull, and Ardnamurchan have shown that there was widespread exchange of oxygen isotopes after the rocks had solidified. This happened between the shallow-level intrusions and low-^{18}O meteoric groundwater (essentially rain and surface water that penetrated deep into the Earth). These fluids interacted extensively with both the volcanic rocks above and the surrounding country-rocks. This hydrothermal activity occurred when hot magma intruded into water-saturated, permeable layers near the surface, setting up hydrothermal circulation systems.

In rocks from Rum, the oxygen isotope values ($\delta^{18}O$) vary widely - from -6.1‰ to +10.7‰. These values infer that both whole-rocks and individual minerals experienced depletion in ^{18}O, especially within the Rum Central Complex and its surrounding contact zone. Rocks further away from the central complex were less affected. This confirms that extensive, post-solidification interaction with low-^{18}O fluids occurred across the intrusive units and the nearby country-rocks.

Within the Layered Suite, oxygen isotope values range from that typical of normal basaltic magmas (positive $\delta^{18}O$) to strongly depleted (negative $\delta^{18}O$). For the surrounding Late Proterozoic Torridon Group rocks (Chapter 2), $\delta^{18}O$ values are high (up to +10.7‰) far from the intrusion but drop near the contact with the intrusion. The lowest values for all rock types are found within 500 m of the margin of the central complex.

In addition to the Layered Suite, the granites have low $\delta^{18}O$ values (from +4‰ down to *ca.* -6‰). However, lavas from the Paleocene Canna Lava Formation (Chapter 6), which were erupted after the central complex formed and was unroofed, retain higher $\delta^{18}O$ values, typical of unaltered basalt (>+6‰). Low $\delta^{18}O$ values in rocks such as gabbros, bytownite-troctolites and peridotites indicate that almost all the ultrabasic rocks were affected by hot, circulating meteoric water.

As noted by Greenwood *et al.* (1992), rocks near the margin of the central complex are highly fractured and brecciated. These rocks have undergone intense hydrothermal alteration at relatively low temperatures. Feldspars have been partially replaced by sericite and the original iron-magnesium minerals have transformed into amphibole or chlorite. These features suggest that the margins of the central complex were zones of high permeability that allowed hydrothermal fluids to circulate efficiently, maximizing oxygen isotope exchange between rock and water.

In contrast, interior parts of the Layered Suite did not experience the same low-temperature alteration. Their original textures and minerals are still intact, suggesting that the isotope exchange occurred at high temperatures - above 450°C (the temperature above which serpentine, a hydrated mineral, is unstable). Despite the significant ^{18}O depletion in feldspar (values from -8.5‰ to +5.9‰) and unusually low oxygen isotope differences between feldspar and pyroxene, the rocks remain being dominated by anhydrous minerals throughout the Eastern Layered Intrusion.

Plagioclase exchanged oxygen isotopes with hot fluids much more readily than pyroxene or quartz. Consequently, some of the variation in $\delta^{18}O$ in the Layered Suite may be due to differences in mineral composition. For example, rocks rich in plagioclase may have lower $\delta^{18}O$ values than those rich in ferromagnesian minerals. One example is Unit 8, where a (lower) peridotite has a $\delta^{18}O$ of +4‰, whereas the overlying bytownite-troctolite has a lower value of +1.8‰ – most likely because of the higher plagioclase content in the troctolite.

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However, mineralogy alone doesn't explain the full range of $\delta^{18}O$ variation seen. Other factors - such as how much fluid the rocks interacted with, how long the interaction lasted, the temperature of the reaction, and changes in fluid composition - must also have played a role. The fact that $\delta^{18}O$ values vary significantly over short distances within units of the Eastern Layered Intrusion suggests that variations in the rock-to-water ratio were the main cause of the observed differences, rather than changes in the isotopic composition of the fluids themselves.

9.9.18 Magma chamber dynamics

Instability of the partly consolidated cumulates within the magma chamber system during its growth is inferred from spectacular slump structures, breccias and unconformable relationships within the ELI and the CI (Figure 9-268). Overall, the magma chamber from which the three intrusions developed, grew in an incremental manner, possibly sill-like in form (Emeleus & Troll 2008), with periodic inputs of magma that have undergone variable degrees of evolution/fractionation in a deeper crustal (or mantle) reservoir. At no stage did the magma chamber have a volume approaching that of the resulting (aggregated) intrusions.

One feasible model is that successive batches of ascending picritic and magnesium-rich basaltic magmas were focused into an approximately N-S zone of weakness on the proto-Long Loch Fault, spreading laterally when they encountered the density trap at the Lewisian Gneiss Complex - Torridonian Supergroup strata boundary (Chapter 2) and crystallising as layered rocks. Later batches intruded and brecciated layered rocks formed earlier and, in turn, spread laterally over the earlier, denser, and now largely crystalline material to build the Eastern and Western layered intrusions.

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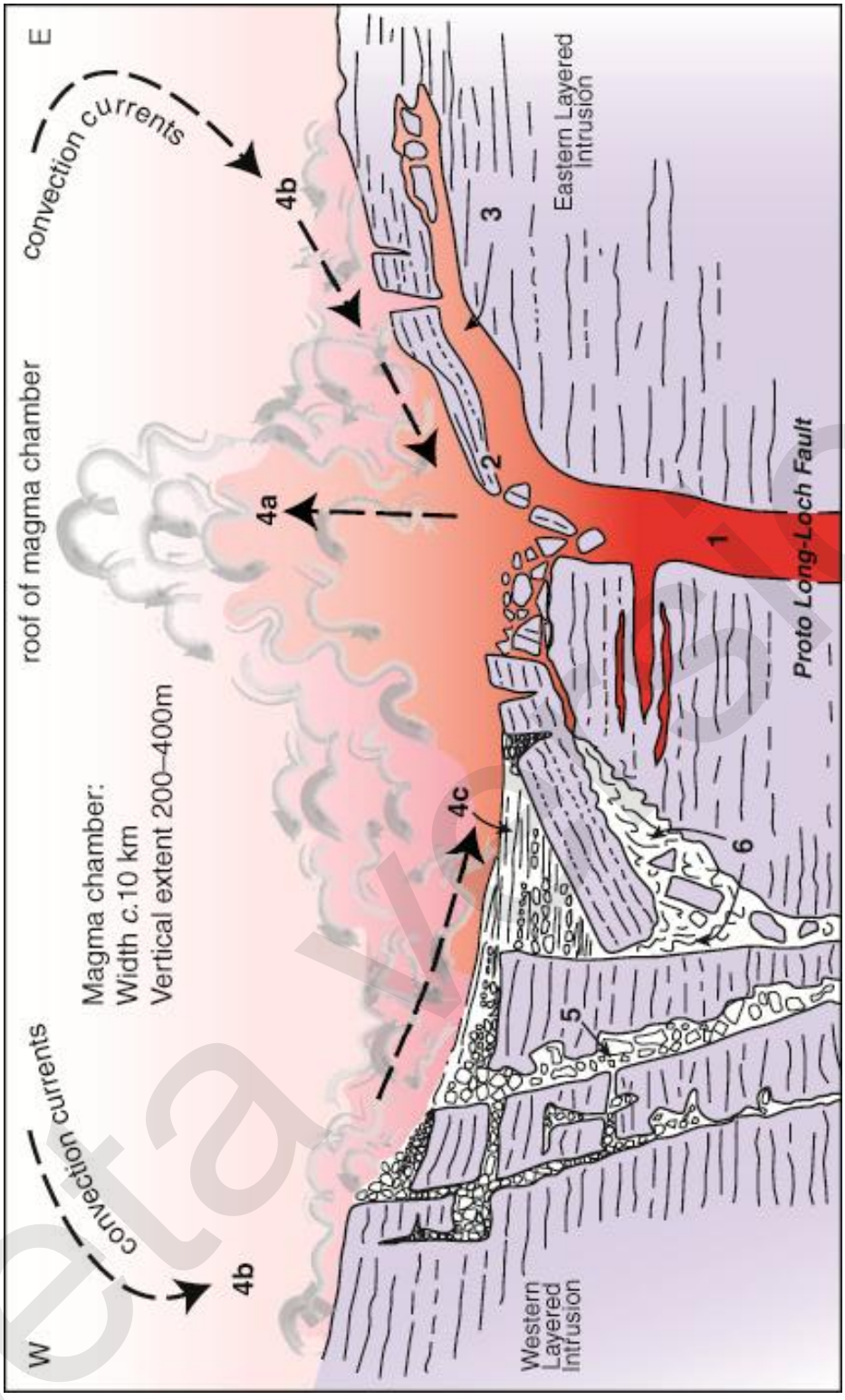


Figure 9-268: Highly schematic representation of possible events leading to the formation of the Central Intrusion. Periodic replenishments of picritic magma (1) rejuvenated the magma chamber causing sliding and slumping and (2) intruded laterally into earlier cumulates leading to partial melting and cumulate recycling (3). Magma fountaining into the chamber (4a) flows off the roof and down the sides as crystal-laden, gravity-driven currents (4b), dislodging crystal mushes as they move, then spread across the floor, reworking cumulate debris and depositing this material and primary crystals on the floor (4c). Movement on faults was accompanied by magma injection, thermal erosion of earlier rocks, fragmentation to form breccia zones and dilation by intrusive brecciation of wall cumulates (5). Slides of coherent blocks of cumulate across partly liquefied cumulate led to spectacular slump mélanges (6).

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9.10 Ardnamurchan

9.10.1 Introduction

The Ardnamurchan Central Complex (ACC) is situated on the Scottish Mainland, north of Mull (Figure 9-1). Three distinct centres of activity have been recognised and numbered sequentially from oldest to youngest as Centre 1, Centre 2 and Centre 3 (Figure 9-269; Figure 9-270; Figure 9-271; Figure 9-272) (Richey & Thomas 1930; Gribble *et al.* 1976). No specific names are attributed to the intrusive centres and there is no obvious spatial progression as the central complex developed: Centre 2 lies to the west of Centre 1, but Centre 3 lies to the NE of Centre 2.

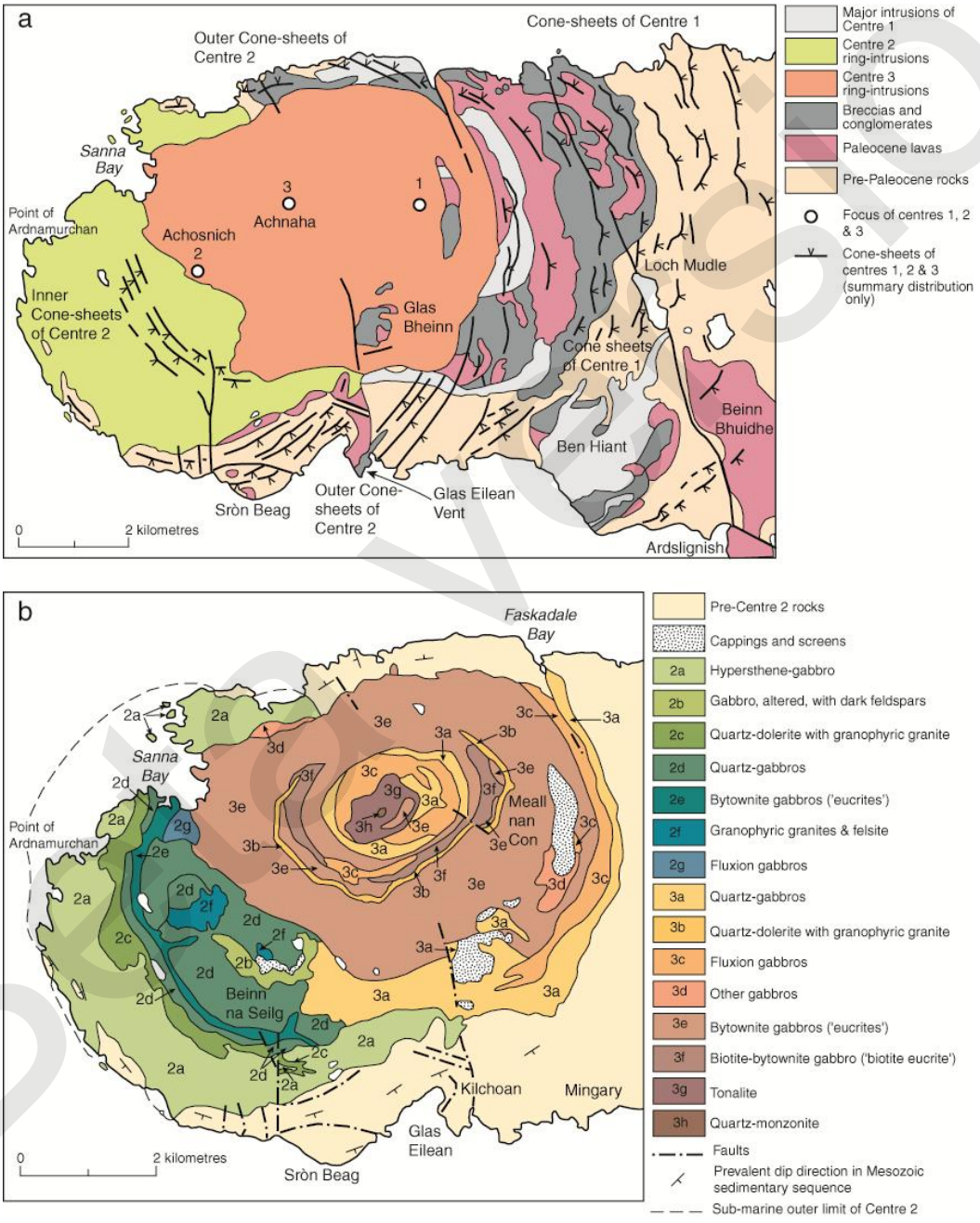


Figure 9-269: Principal components of the Ardnamurchan Central Complex: (a) centres, cone-sheets and country-rocks; (b) ring intrusions of Centre 2 (2a-g) and Centre 3 (3a-h) (after Emeleus & Bell 2005).

Beta Version



Figure 9-270: Google Earth© image of the western end of the Ardnamurchan peninsula.



Figure 9-271: Oblique Google Earth© image of the western end of the Ardnamurchan peninsula. View towards the NE.

Boreview



Figure 9-272: Oblique Google Earth© image of the western end of the Ardnamurchan peninsula. View towards the SE.

The ACC was emplaced into a metamorphic basement of relatively low-grade Moine Supergroup psammites and pelites (Chapter 2), overlain by Triassic breccias, conglomerates and sandstones, Lower Jurassic sandstones, limestones and mudstones (Chapter 3), and Paleocene lavas of the Mull Lava Field (Chapter 6). The proportion of country-rocks to intrusive rocks in the vicinity of Centre 1 is high, whereas centres 2 and 3 are largely devoid of remnants of Pre-Paleocene country-rock between the various major intrusions. The Mesozoic strata and Paleocene lavas have been domed, and dip away from the central complex at *ca.* 30° (Figure 9-269). The doming occurred at an early stage, since it predates cone-sheet emplacement (see below). No marginal annular folds, if they formed (for example, marginal to the Mull Central Complex; see below), are preserved.

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The traditional model that cone-sheets in Ardnamurchan were fed from vertically rising magma beneath the three intrusive centres (Richey & Thomas 1930) is challenged by Magee *et al*. (2012) who, instead, propose a lateral magma supply model, where regional dykes transported magma sideways into cone-sheets. Some cone-sheets appear physically connected to regional sub-vertical dykes, suggesting magma flowed laterally. Furthermore, anisotropy of magnetic susceptibility (AMS) data supports lateral magma flow directions. Rather than a simple cone-sheet system fed from central magma chambers, the Ardnamurchan intrusions may have been assembled from laterally supplied magma.

9.10.2 Centre 1

Along the SE margin of the ACC, on Ben Hiant, a small remnant of the Mull Lava Field is preserved, overlain by *ca*. 200 m of volcaniclastic conglomerates and breccias (Chapter 6). There are no direct links between these volcaniclastic rocks and the nearby ring-intrusions, which define Centre 1.

Interleaved with the Ben Hiant volcaniclastic rocks are sheets of andesitic vitrophyre ('pitchstone' of older literature), typically with well-developed columnar joints. These sheets have previously been interpreted as lavas, although in at least one example on the SE side of Ben Hiant, an intrusive relationship could be inferred, with columnar jointing fanning away from the leading edge of the vitrophyre where it cooled in contact with (possibly water-saturated) conglomerates and breccias. However, Brown *et al*. (2024) conclude that the vitrophyre sheets are ignimbrites that preferentially infilled pre-existing valleys and lakes (Chapter 6). Stratigraphic relationships reveal alternation between incision and infill, highlighting the dynamic interplay of eruption, deposition, erosion, and topographic evolution.

The volcaniclastic rocks on Ben Hiant are invaded by a variety of plagioclase-phyric and non-porphyritic dolerite sheets of unclear association. However, the main intrusive sheets, forming the prominent summit of Ben Hiant and Beinn na h-Urchrach (Figure 9-273; Figure 9-274; Figure 9-275; Figure 9-276; Figure 9-277; Figure 9-278; Figure 9-279; Figure 9-280; Figure 9-281; Figure 9-282; Figure 9-283; Figure 9-284; Figure 9-285; Figure 9-286; Figure 9-287; Figure 9-288), are of a distinctive quartz-dolerite and belong to the Centre 1 set of cone-sheets, with a focal point at depth, *ca*. 1 km west of Meall nan Con (Figure 9-269). The outer members of the set of cone-sheets are inclined inwards at relatively shallow angles (15° to 20°), whereas those towards the interior are inclined at up to 40°. There are also a few multiple and composite (dolerite plus mircogranite 'felsite') cone-sheets.

On the north coast of the Ardnamurchan peninsula, around Achateny and Kilmory, are further outcrops of conglomerate and breccia, cut by the Centre 1 cone-sheets. Other intrusions possibly associated with Centre 1 are shown in Figure 9-269. All are either sheet- or dyke-like and appear to predate the cone-sheets of Centre 1.

Beta version



Figure 9-273: Beinn na h-Urchrach (left) and Ben Hiant (centre). Both summits are dominated by Centre 1 dolerite intrusions. View towards east from Kilchoan.



Figure 9-274: Beinn na h-Urchrach (left of centre) and Ben Hiant (centre). Both summits are dominated by Centre 1 dolerite intrusions. View towards east from Kilchoan.



Figure 9-275: Beinn na h-Urchrach (far left) and Ben Hiant (left of centre). Both summits are dominated by Centre 1 dolerite intrusions. View towards east from Kilchoan.

Beta version



Figure 9-276: Summit crags of Ben Hiant, dominated by Centre 1 (prismatic-jointed) dolerite intrusions. View towards east from Kilchoan.



Figure 9-277: Ben Hiant and Maclean's Nose. View towards west from above Camas nan Geall. On the low ground, Moine Supergroup psammites and pelites are disrupted by Paleocene dolerite intrusions, whilst in the mid ground are horizontally stratified Paleocene lavas and andesitic ignimbrites (vitrophyres, 'pitchstones' of older literature). The summit area is dominated by thick, prismatic-jointed dolerite intrusions of Centre 1. The *ca.* 200 m high cliffs at Maclean's Nose, far left, are composed of Paleocene stratified volcaniclastic strata (conglomerates, breccias, sandstones and siltstones).

Beta version



Figure 9-278: Sròn Mhòr and the western crags of Ben Hiant. On the low ground, Moine Supergroup psammites and pelites are disrupted by Paleocene dolerite intrusions, whilst in the mid ground are horizontally stratified Paleocene lavas and andesitic ignimbrites (vitrophyres, 'pitchstones' of older literature). The summit area is dominated by thick, prismatic-jointed dolerite intrusions of Centre 1. The *ca.* 200 m high cliffs at Maclean's Nose, far left, are composed of Paleocene stratified volcaniclastic strata (conglomerates, breccias, sandstones and siltstones). View towards west from above Camas nan Geall.

Beta Version

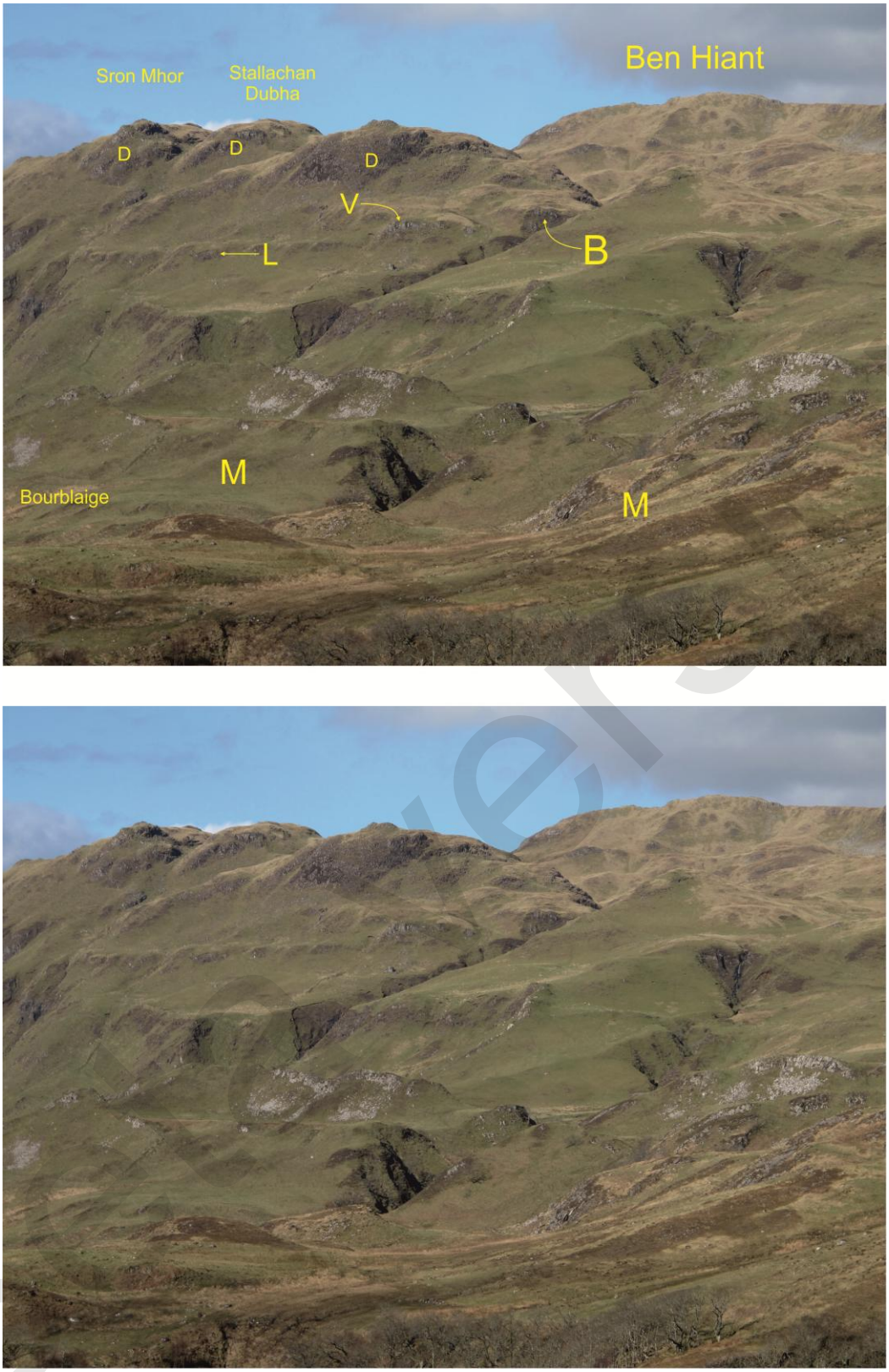


Figure 9-279: Sròn Mhòr, Stallachan Dubha and the western crags of Ben Hiant. Location of abandoned village of Bourblaige indicated. On the low ground, Moine Supergroup psammites and pelites (M) are disrupted by Paleocene dolerite intrusions, whilst in the mid ground are horizontally stratified Paleocene lavas (L) and volcaniclastic sedimentary units, mainly breccias (B) and andesitic ignimbrites (vitrophyres, 'pitchstones' of older literature) (V). The summit areas of Sròn Mhòr, Stallachan Dubha and Ben Hiant are dominated by thick, prismatic-jointed dolerite intrusions (D) of Centre 1. View towards west from above Camas nan Geall.

Preview



Figure 9-280: East side of Ben Hiant and the abandoned village of Bourblaige. On the low ground, Moine Supergroup psammites and pelites are disrupted by Paleocene dolerite intrusions, whilst in the mid ground are horizontally stratified Paleocene lavas and volcaniclastic sedimentary units, mainly breccias, and andesitic ignimbrites (vitrophyres, 'pitchstones' of older literature). The summit area of Ben Hiant is dominated by thick, prismatic-jointed dolerite intrusions of Centre 1. View towards west.



Figure 9-281: East face of Ben Hiant. On the low ground, Moine Supergroup psammites and pelites are disrupted by Paleocene dolerite intrusions, whilst in the mid ground are horizontally stratified Paleocene lavas and volcaniclastic sedimentary units, mainly breccias and andesitic ignimbrites (vitrophyres, 'pitchstones' of older literature). The summit area of Ben Hiant is dominated by thick, prismatic-jointed dolerite intrusions of Centre 1. View towards west.

Beta version



Figure 9-282: Dolerite crags, east side of Ben Hiant (left side). View towards north.



Figure 9-283: Dolerite crags, east side of Ben Hiant. View towards NW.



Figure 9-284: Prismatic-jointed dolerite crags of Sròn Mhòr (left) and Stallachan Dubha (centre), Ben Hiant. The pale horizontal sheet in the middle ground is a prismatic-jointed ignimbrite (vitrophyre, or 'pitchstone' of older literature). People for scale.

Beta version



Figure 9-285: Prismatic-jointed dolerite crags on SW side of Ben Hiant. Ignimbrite (vitrophyre) sheet forms horizontal crag in mid-ground, right-of-centre. View towards the NW.



Figure 9-286: Prismatic-jointed dolerite crags on the SE side of Ben Hiant. View towards north.

Be



Figure 9-287: Prismatic-jointed dolerite cone-sheet on the lower slopes, NE of Ben Hiant. View towards the NW.



Figure 9-288: Inclined, prismatic-jointed dolerite cone-sheets at Tom a' Chapuill, NE of Ben Hiant. View towards the east.

Beta version

9.10.3 Centre 2

Centre 2 was formed by four recognisable phases of intrusive activity, all with a focal point at depth, below Achosnich (Richey & Thomas 1930) (Figure 9-269). The first phase involved the emplacement of an outer (older) set of basic cone-sheets, emplaced into the Mesozoic cover sequence (Chapter 3) and the underlying Moine psammites and pelites (Chapter 2). These cone-sheets are of similar tholeiitic composition to the Centre 1 set, are typically 1 to 5 m thick, and are inclined at 35° to 45° towards the focal point. In the vicinity of Kilchoan, where the distribution density of the cone-sheets is very high (Figure

9-289; Figure 9-290; Figure 9-291; Figure 9-292; Figure 9-293; Figure 9-294), cone-sheets were emplaced into cone-sheets, and in the relatively uncommon instances where country-rock is preserved as screens, it has undergone extreme thermal metamorphism. Multiple and composite members of the set occur but are not particularly common. Emplacement of these outer cone-sheets produced a relative central uplift of *ca*. 1300 m (LeBas 1971), although a degree of central subsidence may also have been involved. In the critical area, near Camphouse, where the outer (older) set of Centre 2 cone-sheets and the Centre 1 cone-sheets occur together, exposure is poor, and it is not possible to establish the order of intrusion. The two sets of cone-sheets are geochemically indistinguishable (Holland & Brown 1972; Geldmacher *et al*. 1998). Burchardt *et al*. (2013), use structural data for the cone-sheets, projected in 3D models, to propose a single, elongate, magmatic system beneath Ardnamurchan, which is consistent with gravity anomaly data (Bott & Tuson 1973).



Figure 9-289: Cone-sheets within Lower Jurassic strata, south coast of Ardnamurchan at Sròn Bheag.



Figure 9-290: Cone-sheet swarm within Moine Supergroup country-rocks. View towards west from promontory at Mingary Pier.



Figure 9-291: Cone-sheet swarm within Moine Supergroup country-rocks. View towards west from promontory at Mingary Pier.

Preview



Figure 9-292: Cone-sheet swarm within Moine Supergroup country-rocks. View towards west from promontory at Mingary Pier.



Figure 9-293: Cone-sheet within Moine Supergroup country-rocks. View towards SW from promontory at Mingary Pier.

Beverst



Figure 9-294: Cone-sheet (left of centre) with inclined prismatic joints within Moine Supergroup psammites (bottom right). View towards SW from promontory at Mingary Pier.

The first major ring-intrusion of Centre 2 is a hypersthene gabbro (Wells 1954) (Figure 9-269, 2a; Figure 9-295; Figure 9-296; Figure 9-297; Figure 9-298; Figure 9-299). This funnel-shaped intrusion (laccolith) is clearly younger than the outer (older) set of cone-sheets, which it cuts at several places along its southern margin, particularly on the south side of Beinn nan Codhan. The hypersthene gabbro has excellent, if uncommon, mineral layering/banding (Figure 9-296; Figure 9-297; Figure 9-298; Figure 9-299). Layers rich in pyroxene, plagioclase and iron-titanium oxides dip inwards towards the focal point but cannot be traced (laterally) far. Augen structures and upward-penetrating finger structures occur in the section north of Sanna Bay and suggest that significant post-cumulus modifications have taken place (cf. Skye and Rum, above).

The thermal effects of the hypersthene gabbro are substantial, with the formation of various rocks of rheomorphic origin from a variety of basement and Mesozoic lithologies. At Glebe Hill, strongly hornfelsed rocks contain a high-grade thermal metamorphic mineral assemblage, with sapphire, spinel and plagioclase, produced from a highly aluminous parent, possibly a Paleocene claystone, or a Jurassic mudstone, or pelitic material from the Moine basement.

Beta Version



Figure 9-295: Lighthouse at the Point of Ardnamurchan, atop the Hypersthene Gabbro. View towards the west.



Figure 9-296: Wavy contact between gabbro variants within the banded Hypersthene Gabbro, south of Sanna Point. Pole *ca.* 1 m long.



Figure 9-297: Detail of wavy contact between gabbro variants within the banded Hypersthene Gabbro. South of Sanna Point. Pole *ca.* 1 m long.



Figure 9-298: Down step within the Hypersthene Gabbro. South of Sanna Point. Pole *ca.* 1 m long.

Preview version



Figure 9-299: Banded structure within the Hypersthene Gabbro, south of Sanna Point. Pole *ca*. 1 m long.

Other Centre 2 intrusions are variants of gabbro and form ridge-like features which partially define their ring geometries (Figure 9-300; Figure 9-301; Figure 9-302; Figure 9-303; Figure 9-304; Figure 9-305; Figure 9-306; Figure 9-307; Figure 9-308; Figure 9-309; Figure 9-310; Figure 9-311).

The gabbro that crops out at Lochan an Aodainn, close to Sonachan, is a thoroughly recrystallised olivine gabbro, severely shattered throughout its mass and with plagioclase crystals that are clouded due to the presence of abundant inclusions of opaque minerals; the clouding has been attributed to thermal alteration. The outcrop pattern is largely controlled by the surrounding younger intrusions and, consequently, its ring shape did not result from its mode of emplacement (Figure 9-269, 2b). The degree of fracturing and alteration present clearly indicate that it was emplaced early in the development of Centre 2.

The Sgùrr nam Meann Ring-dyke (Figure 9-269, 2c) is a hybrid intrusion, consisting of dolerite veined by microgranite and felsite (or net-veined gabbro of some literature). It crops out in an arc over *ca*. 6 km south and SE of Sanna Bay. This intrusion, most likely a steep-sided, outward-dipping ring-dyke, was formed by the turbulent mixing of basaltic and silicic magmas (Blake *et al.* 1965; Skelhorn & Elwell 1966). Typically, the silicic material either forms veins (millimetre to centimetre wide) within large masses of dolerite, resulting in relatively angular outlines to the dolerite 'clasts', or acts as 'matrix' to more rounded, pillow-like masses of dolerite (Figure 9-300; Figure 9-301; Figure 9-302; Figure 9-303; Figure 9-304; Figure 9-305; Figure 9-306; Figure 9-307; Figure 9-308; Figure 9-309; Figure 9-310). In the latter situation, thin, irregular (crenulated), chilled margins to the dolerite indicate that the basaltic material was liquid when it came into contact with the silicic magma. Thus, on interacting, the hot basaltic magma underwent rapid cooling and crystallisation (or, locally, quenching to a glass) against the cooler but still liquid silicic magma,

forming 'pillows' of dolerite with chilled, glassy (tachylitic) margins. Contraction cracks formed on the edges of some pillows, and silicic magma was then injected into these and beyond, resulting in veining and fragmentation of the dolerite.



Figure 9-300: The Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), Eilean Carrach. View north towards Muck and (beyond) Rum.



Figure 9-301: The Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), Eilean Carrach. View north towards Muck and (beyond) Rum.

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Figure 9-302: The Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), Eilean Carrach. View towards east.



Figure 9-303: The Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Pole *ca.* 1 m long.



Figure 9-304: Detail of the Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Pole *ca*. 1 m long.



Figure 9-305: Detail of the Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Pole *ca*. 1 m long.

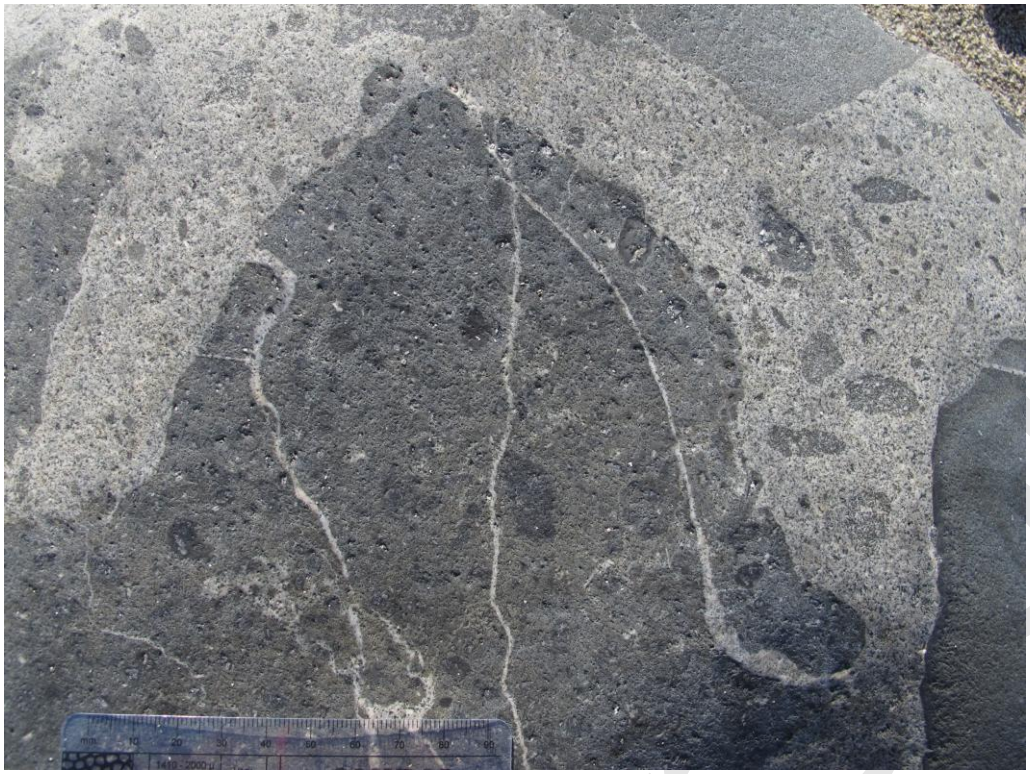


Figure 9-306: Detail of the Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Ruler for scale.

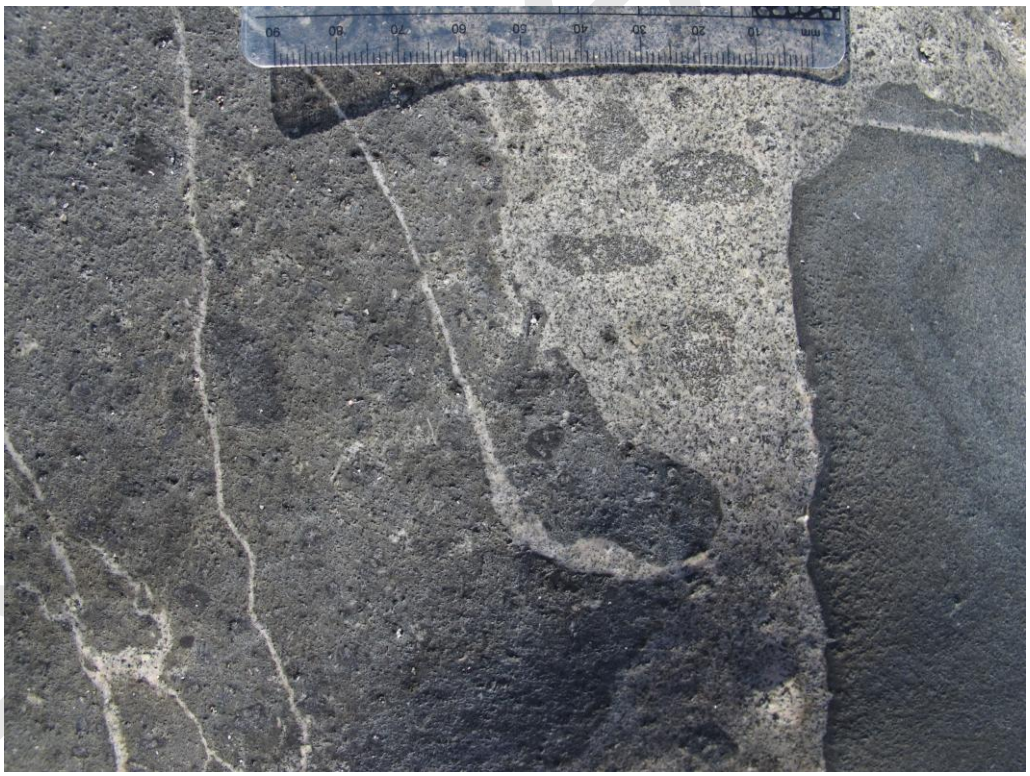


Figure 9-307: Detail of the Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Ruler for scale.

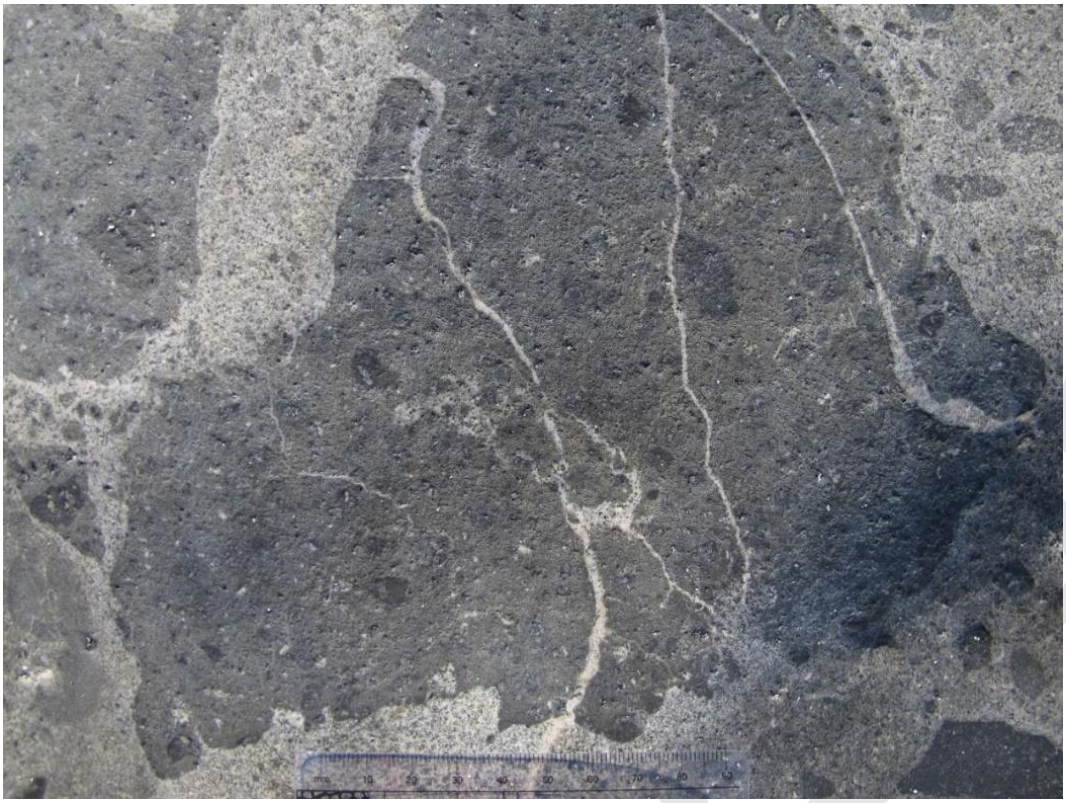


Figure 9-308: Detail of the Sgùrr nam Meann Ring-dyke, or 'quartz dolerite with granophyric granite' (or net-veined gabbro of some literature), north side of the bay of Eilean Carrach. Ruler for scale.



Figure 9-309: Detail of chilled margin to dolerite 'pillow' within a granophyric granite 'matrix', north side of the bay of Eilean Carrach. Ruler for scale. Ruler for scale.



Figure 9-310: Granophyric microgranite veins within dolerite 'pillow', north side of the bay of Eilean Carrach. Ruler for scale.

Within Centre 2 there are several other less complete ring-intrusions that predate the inner basic cone-sheets (see below). They comprise quartz-dolerites and gabbros, a granite and various felsites (Figure 9-269 2d, 2e, 2f & 2g and Figure 9-311**;** Figure 9-312**;** Figure 9-313**;** Figure 9-314**;** Figure 9-315**;** Figure 9-316**;** Figure 9-317**;** Figure 9-318**;** Figure 9-319**;** Figure 9-320) and have not been studied in detail since the original survey of Richey & Thomas (1930).

Beta version



Figure 9-311: Twin peaks of Beinn na Seilg, composed of Centre 2 quartz gabbros, viewed along the south coast of Ardnamurchan from Ben Hiant. View towards west.



Figure 9-312: Lighthouse at Point of Ardnamurchan (Hypersthene Gabbro), and Loch Grigadale - Sgurr nam Meann - Beinn Bhuidhe (left to right) (quartz gabbro(s)) from Beinn na Seilg. View towards west.

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Figure 9-313: Summit area of Beinn na Seilg (quartz gabbro). View north towards Beinn Bhuidhe (left of centre), and beyond to Muck, Eigg and the mountains of Rum.

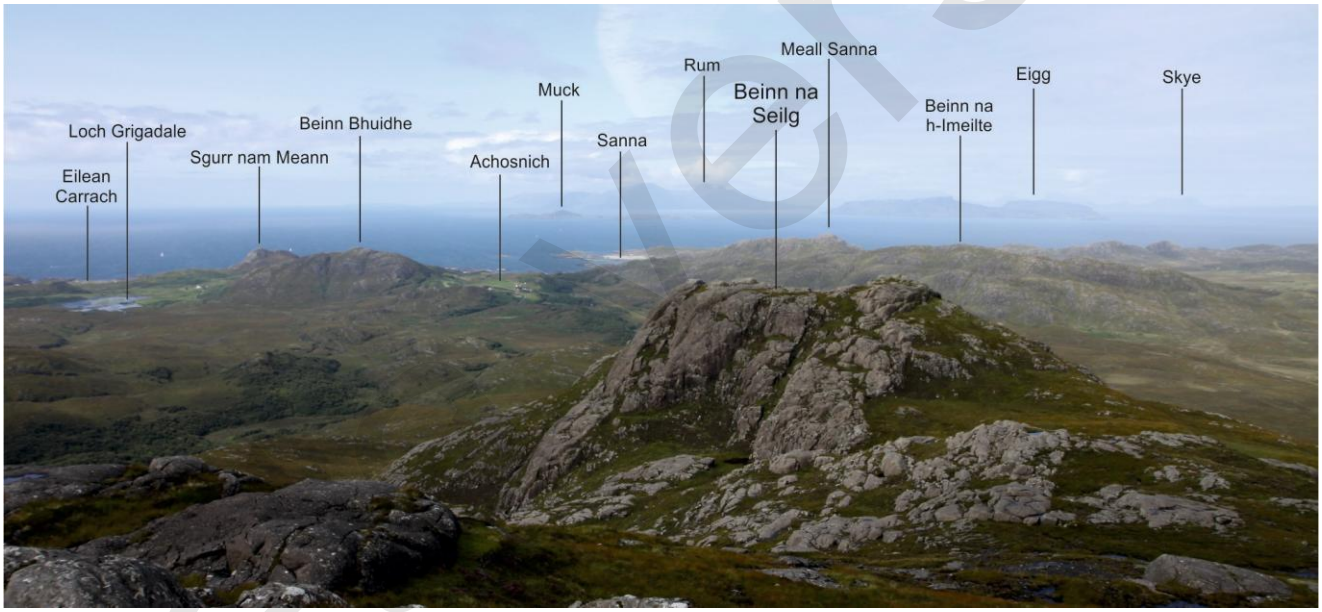


Figure 9-314: Sgurr nam Meann, Beinn Bhuidhe, Beinn na h-Imeilte and Meall Sanna from Beinn na Seilg (quartz gabbro). View towards north.

Beta version



Figure 9-315: Summit of Beinn na Seilg (coarse-grained, heterogeneous quartz gabbro). View east towards Ben Hiant.



Figure 9-316: Summit of Beinn na Seilg (quartz gabbro). View NW towards Ardnamurchan lighthouse.

Be



Figure 9-317: Homogeneous, ice-moulded quartz gabbro, Beinn na Seilg. View NW towards Loch Grigadale.



Figure 9-318: Detail of banded structure in quartz gabbro on Beinn na Seilg. Pole *ca*. 1 m long.



Figure 9-319: Detail of banded structure in quartz gabbro on Beinn na Seilg. Pole *ca.* 1 m long. View towards east.



Figure 9-320: Detail of granitic veins and breccia development in quartz gabbro of Beinn na Seilg. Pole *ca.* 1 m long.

From a study of gabbroic inclusions within some of the Centre 2 intrusions, including the hypersthene gabbro, Magee *et al*. (2013) concluded that the inclusions are not part of the same batch of magma, although their magnetic fabrics match, suggesting synchronous flow from a deeper reservoir. Entrainment of the inclusions triggered a transition from Newtonian to Bingham-like magma rheology, with the magma becoming more viscous and slower flowing, thus enabling the inclusions to be entrained and transported. An estimation of settling velocities and rheological properties indicate that even after merging, magma flow remained zoned, dynamically complex, and locally variable.

The third phase of intrusive activity associated with Centre 2 was the emplacement of the inner (younger) basic cone-sheets. These intrusions are steeply inclined inwards, at up to 70°, towards the focal point below Achosnich. They are typically plagioclase-phyric dolerites.

The final phase of intrusive activity in Centre 2 was the emplacement of a further set of incomplete ring-intrusions, mainly of quartz gabbro, some of which have a fabric due to the alignment of plagioclase (the so-called fluxion structure, or lamination, of Richey & Thomas 1930). Whether certain of these intrusions are late-stage members of Centre 2 or early members of Centre 3 is not clear.

The formation of the Glas Eilean Vent (Figure 9-269), cropping out on the east side of the narrow promontory and tidal island on the east side of Kilchoan Bay, was later than the intrusion of the outer basic cone-sheets, but possibly contemporaneous with the development of the younger intrusions of Centre 2. The outcrop of the vent material is partly fault-bounded, with Moine basement rocks along the SE margin and basaltic lavas to the west. The fragmental material within the vent consists of blocks of Moine Supergroup psammite and pelite, Jurassic sandstone and limestone, and various basic igneous rock-types (porphyritic and non-porphyritic dolerite and basalt, some possibly derived from the outer cone-sheets). Much of the fragmental material appears to have been brecciated almost *in situ* and not subsequently transported any significant distance. The matrix that binds the blocks together forms vein-like features, up to 0.5 m across, with fine-grained margins against the blocks. It is composed of comminuted block material together with pumiceous and shard-like fragments of devitrified (silicic?) glass. The vein-like features form an anastomosing network and were most likely formed when pyroclastic material was emplaced during rapid volatile escape. Degassing may have been responsible primarily for the initial and subsequent brecciation of the blocks.

9.10.4 Centre 3

The youngest intrusive centre within the Ardnamurchan Central Complex comprises annular gabbroic intrusions with near-complete ring geometries (Figure 9-269). The dips of the inter-intrusion contacts are most likely inwardly inclined and give rise to a nested set of funnel-shaped intrusions. Fabrics due to plagioclase alignment ('fluxion structures') help to distinguish between some of the intrusions. The focal point of Centre 3 is *ca*. 1 km ENE of Achnaha, directly below the compositionally evolved intrusions (Figure 9-269). The centre is slightly ovoid, measuring *ca*. 7 km ENE and 6 km NNW. The margin of the centre is defined by various relatively small gabbros with outcrops that define sectors of ring-intrusions. However, the largest of the Centre 3 intrusions and the one which helps to define its overall geometry and give it topographic expression, is the so-called Great Eucrite (Figure 9-269, 3e), a bytownite olivine-gabbro, which forms an arc of high ground (Figure 9-270; Figure 9-271; Figure 9-272 and Figure 9-321; Figure 9-322; Figure 9-323**;** Figure 9-324**;** Figure 9-325**;** Figure 9-326**;** Figure 9-327**;** Figure 9-328). The outcrop width of the Great Eucrite is *ca*. 1 km and the external diameter of the intrusion is between 4.5 and 6 km. Thus, if it were a true ring-dyke (the interpretation of Richey & Thomas 1930), dipping steeply outwards (compare with Figure 9-22), unrealistically large amounts of central subsidence would have been required. More

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likely, the Great Eucrite, together with other gabbroic intrusions of Centre 3, constitute a composite intrusion of lopolithic or funnel-like shape.

O'Driscoll *et al*. (2006) challenged the long-standing interpretation that the Great Eucrite is a ring-dyke intrusion formed by cone-collapse and subsequent magma upwelling. Instead, they present new field and structural evidence demonstrating that the intrusion is better described as a lopolith - a shallow, saucer-shaped magma body that intruded laterally. Key observations include: contacts between the Great Eucrite and surrounding rocks are mostly concordant, not steeply inclined or vertical as expected in a ring-dyke; internal mineral layering, albeit uncommon, dips inward, consistent with gravitational settling in a lopolithic body; and, a lack of structural features (such as brittle faults or collapse breccias) associated with caldera ring-dyke formation.

One of the most remarkable features of the Great Eucrite is that, given its relatively large volume, it is largely, but not wholly, devoid of internal structure; layering, mineral fabric, xenoliths and pegmatites are uncommon, perhaps implying that the intrusion had an uncomplicated emplacement history (Figure 9-325; Figure 9-326; Figure 9-327; Figure 9-328).



Figure 9-321: Meall Clach an Daraich in the NW sector of the Great Eucrite. View towards NW from the approximate middle of Centre 3, with the peaks of Rum in the distance.

Beta version



Figure 9-322: Meall Sanna in the western sector of the Great Eucrite. View towards the west from the approximate middle of Centre 3, with the ridge of An Sgùrr on the island of Eigg in the distance.



Figure 9-323: Meall Clach an Daraich and Sgùrr nan Gabhar in the northern sector of the Great Eucrite. View towards NW from Meall Meadhoin.



Figure 9-324: Beinn na h-Imeilte in the SW sector of the Great Eucrite. View towards SW from Meall Meadhoin.



Figure 9-325: Banded structure within the eastern sector of the Great Eucrite. Pole *ca*. 1 m long.



Figure 9-326: Banded structure within the eastern sector of the Great Eucrite. Pole *ca*. 1 m long.



Figure 9-327: Inclined mineralogical banding/stratification within the Great Eucrite. Pole *ca*. 1 m long.



Figure 9-328: Inclined mineral fabric within the Great Eucrite. Coin *ca*. 24 mm across.

Within the interior of Centre 3 is a hybrid intrusion that was formed by the partial mixing of basic and silicic magmas (Figure 9-269, 3b). This narrow, steep-sided intrusion crops out over about 270° of arc, suggesting off-centre subsidence of the central block or some form of rotational or 'trap door' subsidence mechanism for its emplacement. Certain of the gabbroic ring-intrusions within the inner part of Centre 3 crop out over the same sector as this ring-dyke.

The innermost part of Centre 3, directly above the focal point, is composed of a small area of amphibole-rich tonalite and a central mass of quartz monzonite with large biotite crystals (Figure 9-269, 3g, 3h). Given their position within Centre 3 and their hybrid mineralogical and compositional characteristics, it is likely that these evolved rocks are the product of reaction between fractionating basaltic magmas and partially melted roof rocks (Gribble *et al.* 1976; Geldmacher *et al.* 2002). Radiometric age determinations on the tonalite and Great Eucrite give ages of *ca*. 59 Ma (Chapter 5).

There are very few minor intrusions spatially associated with Centre 3, limited to sparse dolerite cone-sheets cutting the older members of the centre in the south, and a few NNW-SSE-trending dykes that cut the younger ring-intrusions.

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9.11 Mull Central Complex (MCC)

9.11.1 Introduction

Our understanding of the sequence of intrusive events in the Mull Central Complex (Figure 9-1) (MCC) is still largely based on the work of Bailey *et al.* (1924). Since then, only a few detailed studies have focused on the major intrusions, along with a brief overview and field guide provided by Skelhorn & Longland (1969).

Three main intrusive centres have been identified and are designated as Centres 1, 2, and 3 (Figure 9-329). Centres 1 and 3 are associated with the development of calderas - Centre 1 with the Early Caldera (also known as the Glen More Centre), and Centre 3 with the Late Caldera (or Loch Bà Centre). Centre 2, the Beinn Chaisgidle Centre, is characterised by cone-sheet and ring-dyke intrusions.

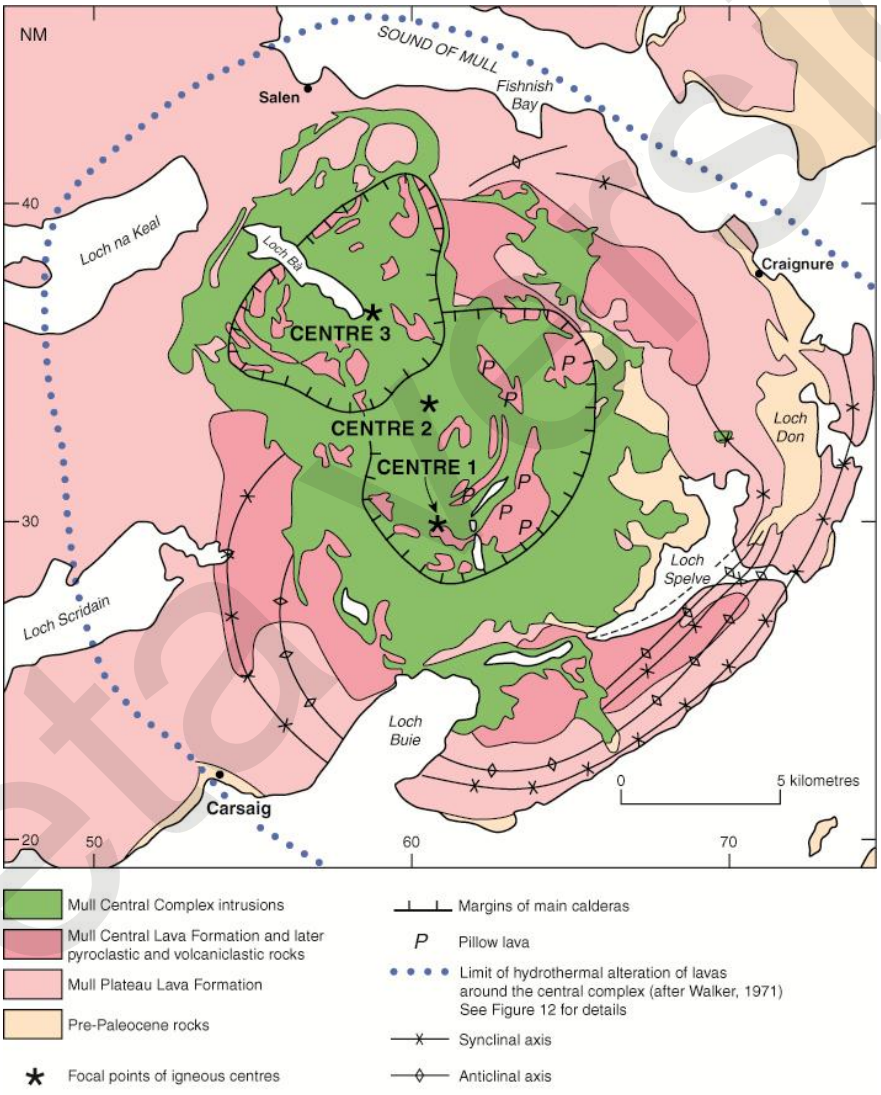


Figure 9-329: Simplified geological map of the principal components of the Mull Central Complex (after Emeleus & Bell 2005).

During the formation of the MCC, magmatic activity gradually shifted from Centre 1 to Centre 3 (Figure 9-330), moving several kilometres in a SE to NW direction, which is roughly parallel to the trend of the Mull

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Regional Dyke Swarm (Chapter 7). Large annular folds surround the intrusive complex, affecting both Mesozoic sedimentary units and Paleocene basaltic lavas. The spatial distribution of the folds aligns with the Glen More Centre, suggesting emplacement of magma into shallow crust, causing uplift and deformation (Bailey 1962), with the possibility that some of the deformation events are due to the development of two younger intrusive centres.

9.11.2 Centre 1: The Glen More Centre

9.11.2.1 Introduction

Within the MCC, remnants of pillowed basaltic lavas are preserved and serve in part as country-rock for later intrusions. Their relationship to the main Mull Lava Field is uncertain, but Bailey *et al.* (1924) suggest that these pillow lavas represent the youngest stratigraphic part of the field, formed within a caldera. This interpretation supports the identification of Centre 1 as the Early Caldera (Figure 9-329). These lavas are referred to as the 'Non-Porphyritic Central Magma Type' or 'Central Mull Tholeiites' (see Chapters 6 and 10).

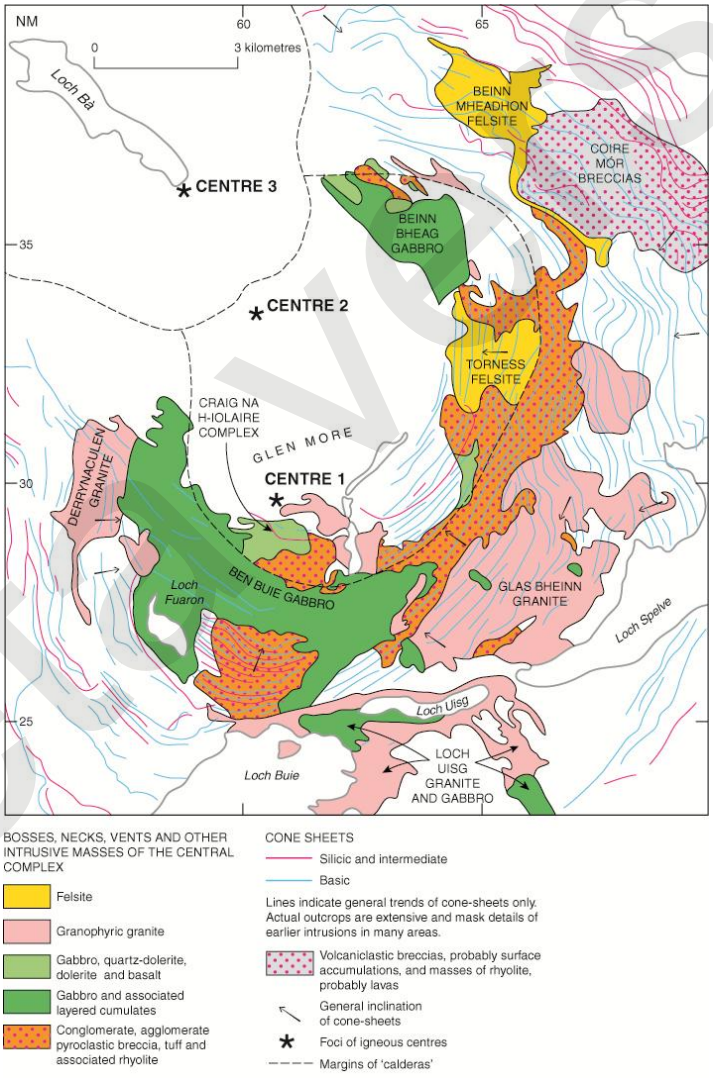


Figure 9-330: Simplified geological map of Centre 1, the Glen More Centre (and Early Caldera), Mull Central Complex (after Emeleus & Bell 2005).

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9.11.2.2 Early granites

The oldest major intrusions of the Glen More Centre are the steep-sided granites of Glas Bheinn and Derrynaculean and may represent components of ring-dykes or steep-sided stocks. Their emplacement was partly controlled by ring-faults and central collapse structures. Extensive brecciation, most likely caused by either gas escape or ring-faulting, is observed throughout the granite bodies, particularly in the Derrynaculean intrusion.

The Glas Bheinn Granite was intruded into the core of the marginal Loch Spelve Anticline, which is imperfectly developed. Both granite bodies show significant hydrothermal alteration, with primary pyroxene replaced by chlorite or uralite. The margins of the Glas Bheinn Granite also contain partially assimilated siliceous material, most likely derived from Triassic sandstone country-rocks (Chapter 3).

9.11.2.3 Explosion breccias

Several masses of breccia occur along the ring-fault that outlines the Early Caldera (Figure 9-330). The best exposures occur in the SE part of the fault zone, especially on the eastern side of Sgùrr Dearg. These breccias consist of subangular to rounded fragments of Paleocene lavas, Mesozoic sedimentary rocks, Moine gneisses, and various coarse-grained igneous rocks such as gabbro and granite, and are interpreted to have formed by some form of 'explosive' process, most likely involving vapour expansion from crystallizing magma(s).

Notably, Moine gneiss fragments are generally absent from within the main caldera boundary, implying that the basement rocks lie at a deeper structural level beneath the caldera. This suggests that explosive brecciation occurred at relatively shallow crustal levels. The breccias also include fragmented rhyolitic rocks with flow-banded and perlitic textures, most likely formed by gas streaming from silicic magmas. Surface volcanic deposits associated with this explosive activity are not recognised, possibly due to subsequent erosion.

On the eastern side of the caldera, at Coire Mór, an outcrop of generally unstratified volcaniclastic breccia contains subangular to rounded blocks of Paleocene igneous rocks and older sedimentary rocks. Large flow-banded rhyolite masses are also present. Similar breccias are found at Barachandroman, on the southern shore of Loch Spelve. Bailey *et al.* (1924) interpreted the Coire Mór deposits as surface accumulations, possibly formed alongside rhyolite lava flows. However, Richey (1961) proposed that they resulted from subsurface gas-driven brecciation, similar to the explosion breccias observed at Sgùrr Dearg.

9.11.2.4 Early felsites

The flow-banded felsites of Beinn Mheadhon, Torness, and Creag na h-Iolaire were most likely contemporaneous and were emplaced prior to the explosion breccias. While the Beinn Mheadhon Felsite lies outside the caldera-bounding fault, the other two are located within it. These felsites are crosscut by later basic intrusions, mostly cone-sheets, which obscure their original geometry.

9.11.2.5 Early cone-sheets

An early suite of cone-sheets intruded the Glas Bheinn and Derrynaculean granites, the explosion breccias, and the early felsites (see above). These cone-sheets are predominantly basic in composition, although a minority are intermediate to silicic (Figure 9-331; Figure 9-332). They dip inward at *ca.* 45°, converging toward a focal point beneath Beinn Chaisgidle, and have a combined thickness approaching

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1,000 m, with individual sheets up to 10 m thick. Their emplacement caused significant central uplift. The main outcrop forms an arcuate belt from Glen Forsa in the north, near Loch Spelve, across Glen More to Derrynaculean.

The precise timing of the intermediate and silicic sheets relative to the basic sheets is uncertain, but overlaps are evident: composite cone-sheets of both types exist. The fault defining the Early Caldera had ceased movement by the time that these early cone-sheets were emplaced.



Figure 9-331: Composite cone-sheet, Glen More Centre, at Barr Shòmhairle, south of Grass Point. [Photograph courtesy of James Westland]



Figure 9-332: Magma mingling in an Early Acid (silicic) cone-sheet, Glen More Centre. [Photograph courtesy of James Westland]

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9.11.2.6 Gabbros

Following the intrusion of the early cone-sheets, two major gabbroic bodies were emplaced: the Ben Buie Gabbro in the SW (outside the main ring-fault) (Figure 9-333; Figure 9-334; Figure 9-335; Figure 9-336; Figure 9-337; Figure 9-338; Figure 9-339; Figure 9-340; Figure 9-341; Figure 9-342; Figure 9-343; Figure 9-344; Figure 9-345), and the Beinn Bheag Gabbro in the NE (inside the main ring fault). The Ben Buie intrusion may have used the ring-fault for emplacement. Skelhorn & Longland (1969) suggest that both the Ben Buie Gabbro and the Corra-bheinn Gabbro, the latter of the Loch Bà Centre (see below), were originally circular in plan and that central subsidence later removed parts of them to greater depths.

Mineral layering within the Ben Buie Gabbro dips inward, steepening from 15°–20° at the margins to over 35° near the ring-fault. The outer SE margin dips gently outward, but the inward-dipping layers suggest the base is not far below. The gabbro's chilled margin is tholeiitic basalt, similar to the Mull cone-sheets (Chapter 10), indicating a genetic connection. The cumulate layers vary from olivine-rich peridotite to plagioclase-dominated troctolite and bytownite-troctolite. Chrome-spinel-rich layers are common in the ultrabasic zones.

Bailey *et al.* (1924) distinguished different facies within the Beinn Bheag Gabbro based on crystal size and mineralogy, including a marginal facies veined with silicic material and a brecciated zone. Xenoliths, both cognate (unaltered) and recrystallized, are widespread (Figure 9-337; Figure 9-338; Figure 9-339). The gabbros were later intruded by cone-sheets ranging from basic to silicic, belonging to Centre 2.



Figure 9-333:: Ben Buie from the summit of Ben More. View towards the SE.

Beta version



Figure 9-334: Layered troctolite and gabbro in the Ben Buie Gabbro, east corrie of Benn Buie. [Photograph courtesy of John Faithfull]



Figure 9-335: Layered Ben Buie Gabbro, east corrie of Ben Buie. [Photograph courtesy of John Faithfull]

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Figure 9-336: Layered Ben Buie Gabbro, close to the summit of Ben Buie. [Photograph courtesy of John Faithfull]



Figure 9-337: Grey gabbro xenoliths/blocks in brown host gabbro, Ben Buie, W of the 717 m summit. [Photograph courtesy of John Faithfull]

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Figure 9-338: Detail of grey gabbro xenoliths/blocks in brown host gabbro, Ben Buie, W of 717 m summit. GPS unit *ca.* 15 cm long. [Photograph courtesy of John Faithfull]



Figure 9-339: Anorthosite xenolith with chromite rim in the Ben Buie Gabbro. Hand lens *ca.* 10 cm long. [Photograph courtesy of John Faithfull]



Figure 9-340: Chromite layers within the Ben Buie Gabbro. GPS unit *ca.* 15 cm long. [Photograph courtesy of John Faithfull]



Figure 9-341: Rhythmically layered Ben Buie Gabbro, NW of Craig, Glen More. GPS unit *ca.* 15 cm long. [Photograph courtesy of John Faithfull]

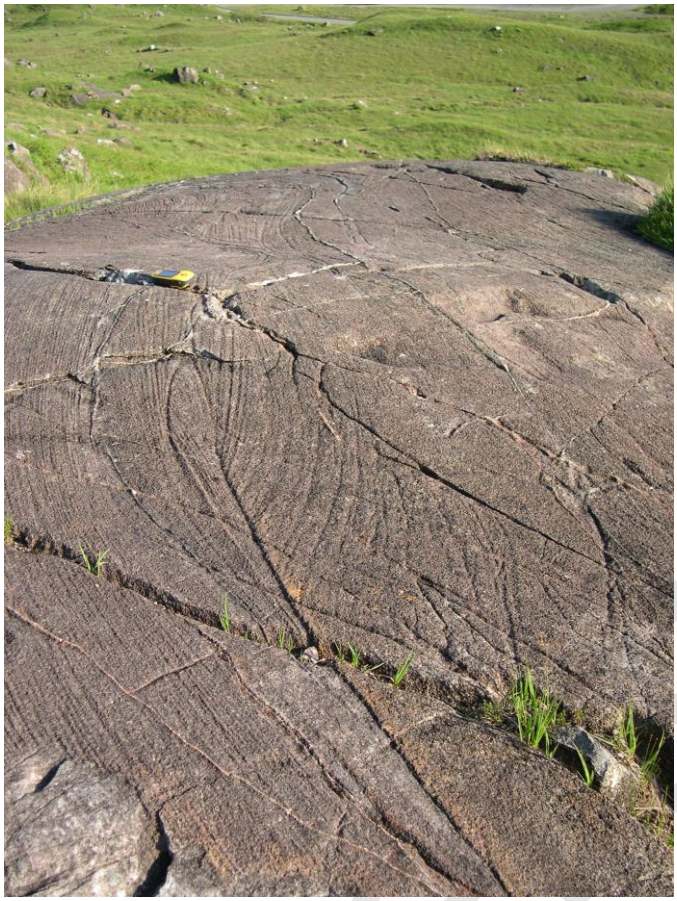


Figure 9-342: Detail of rhythmically layered Ben Buie Gabbro, NW of Craig, Glen More. GPS unit *ca*. 15 cm long. [Photograph courtesy of John Faithfull]

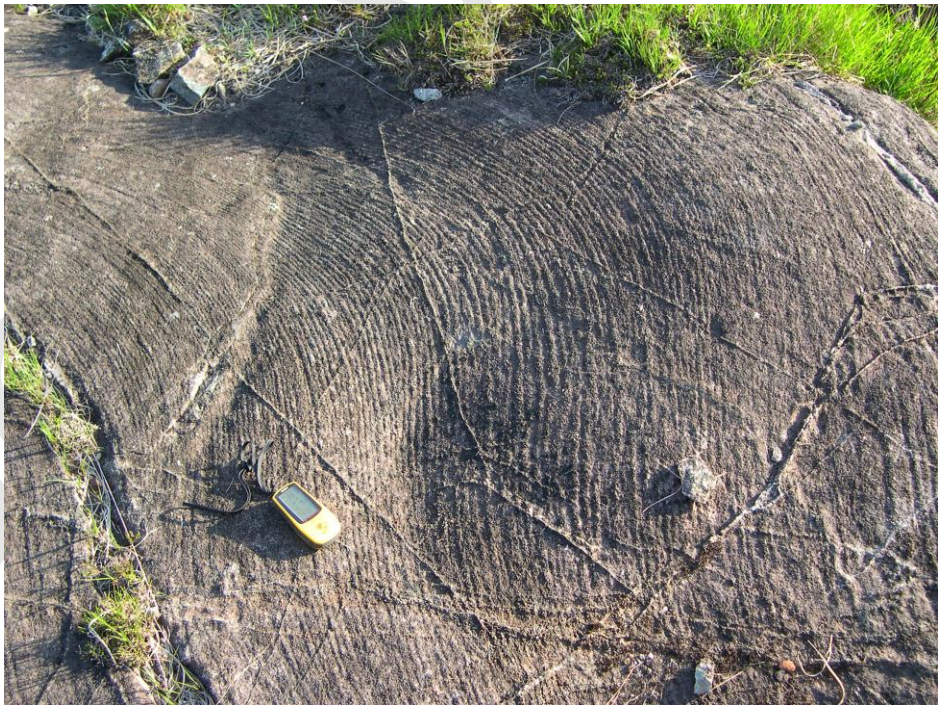


Figure 9-343: Detail of rhythmically layered Ben Buie Gabbro, NW of Craig, Glen More. GPS unit *ca*. 15 cm long. [Photograph courtesy of John Faithfull]

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Figure 9-344: Streaky, deformed troctolite within the Ben Buie Gabbro, east side of Ben Buie. [Photograph courtesy of John Faithfull]



Figure 9-345: 'Channel' within banded troctolite, Ben Buie Gabbro, east side of Ben Buie. Hammer *ca.* 30 cm long. [Photograph courtesy of John Faithfull]

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Figure 9-346: Graded layering, Ben Buie Gabbro. Boulder. Pencil *ca.* 15 cm long. [Photograph courtesy of John Faithfull]

9.11.2.7 The Loch Uisg Granite - Gabbro Intrusion

This composite intrusion comprises gabbroic (olivine-gabbro to olivine-dolerite) and granitic lithologies (Figure 9-347; Figure 9-348; Figure 9-349; Figure 9-350; Figure 9-351; Figure 9-352; Figure 9-353; Figure 9-354). The granite has a granophyric texture where in contact with the gabbro and where hybrid rocks have formed by magma mingling/mixing. The intrusion is essentially a flat-lying sheet, emplaced into Paleocene lavas, although at the western end of Loch Uisg, the granite's upper contact dips steeply northwards. At the eastern end, its roof is made up of volcaniclastic breccias (see above), which are thermally altered and recrystallized. The intrusion postdates the annular folds and explosion breccias of the Glen More Centre. Its relationship to early cone-sheets is ambiguous: it is both cut by and cuts various sheets. Overall, it is considered to be one of the later intrusions of the Glen More Centre.

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Figure 9-347: Layered Loch Uisg Gabbro, Creag nam Fitheach, SE of Loch Uisg. Poles *ca*. 1 m long. [Photograph courtesy of James Westland]



Figure 9-348: Xenolithic Loch Uisg Gabbro, Creag nam Fitcheach, SE of Loch Uisg. Ruler 30 cm long. [Photograph courtesy of James Westland]

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Figure 9-349: Loch Uisg Granophyre, intruded by cone-sheets (bottom left to top right), all intruded by a thin inclined dyke, SE of Loch Buie. [Photograph courtesy of James Westland]



Figure 9-350: Loch Uisg Gabbro. [Photograph courtesy of John Faithfull]

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Figure 9-351: Laggan Bay pegmatite pod in the Loch Uisg Gabbro [Photograph courtesy of John Faithfull]



Figure 9-352: Spherulitic margin to cone-sheet in Loch Uisg Gabbro, Laggan Bay. [Photograph courtesy of John Faithfull]

Beta version



Figure 9-353: Pelitic xenolith, most likely either Dalradian or Moine supergroup meta-sedimentary material, in the Loch Uisg Gabbro. The xenolith was melted, maintained its physical integrity, and upon cooling solidified to glass (i.e. a buchite). Laggan Bay, south Mull. [Photograph courtesy of John Faithfull]



Figure 9-354: Detail of pelitic xenolith, most likely either Dalradian or Moine supergroup meta sedimentary material, in the Loch Uisg Gabbro. The xenolith was melted, maintained its physical integrity, and upon cooling solidified to glass (i.e. a buchite). Laggan Bay, south Mull. [Photograph courtesy of John Faithfull]

9.11.3 Centre 2: The Beinn Chaisgidle Centre

9.11.3.1 Introduction

Following the formation of the Glen More Centre, igneous activity migrated a few kilometres NW to the Beinn Chaisgidle area. This new focus, Centre 2, is characterized by steeply inclined, outward-dipping ring-dykes (ranging from basalt to rhyolite) and inward-dipping cone-sheets of basalt and dolerite (Figure 9-355).

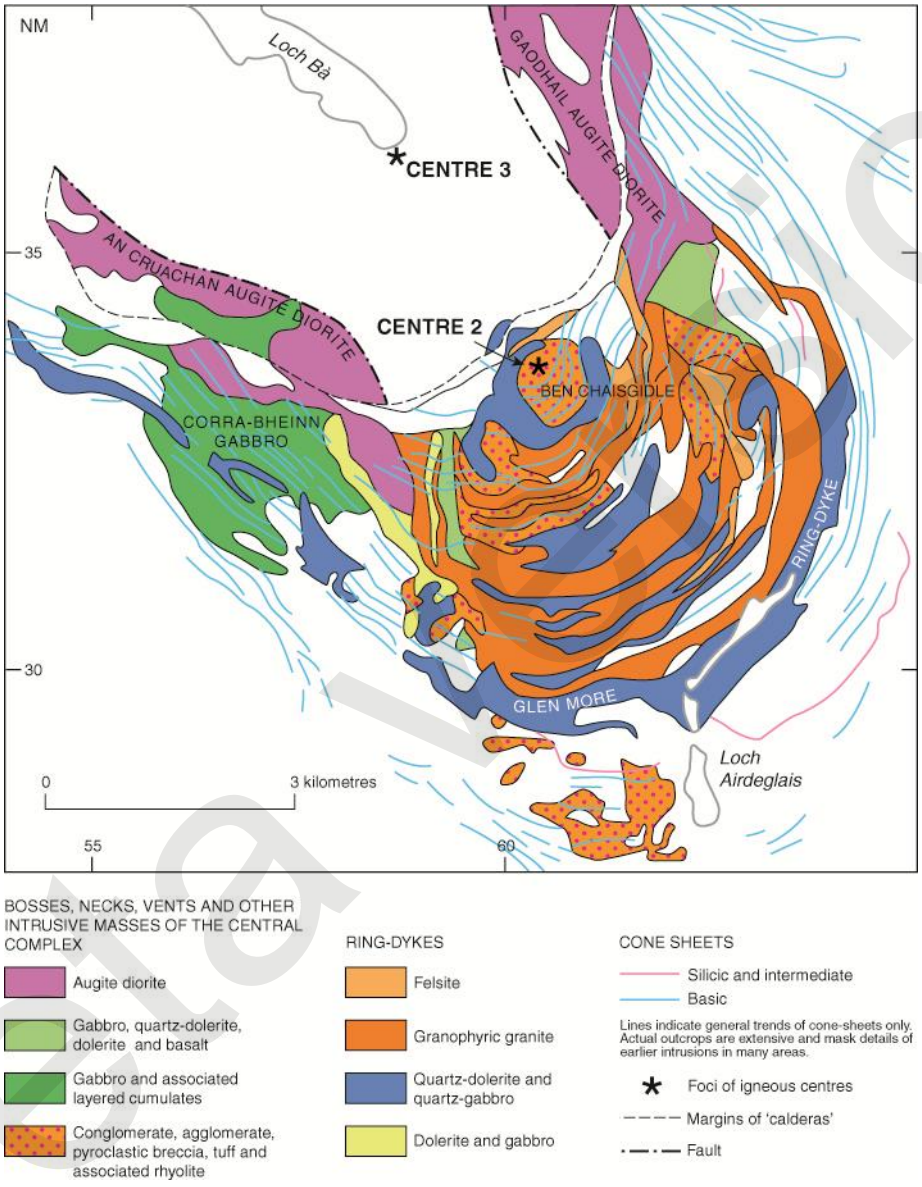


Figure 9-355: Simplified geological map of Centre 2, the Beinn Chaisgidle Centre, Mull Central Complex (after Emeleus & Bell 2005).

9.11.3.2 Corra-bheinn Gabbro

Located to the west, largely outside the Early Caldera's ring-fault, the Corra-bheinn Gabbro displays layered structures dipping towards the NE at angles between 25° and 80° (Figure 9-356; Figure 9-357). Though it might be a late feature of Centre 1, its intrusion postdates early cone-sheets (which cut the Ben Buie Gabbro), so it is provisionally attributed to Centre 2.

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Figure 9-356: Steeply inclined stratification of the Coire-bheinn Gabbro, SW of the summit of Coire-bheinn. [Photograph courtesy of John Faithfull]



Figure 9-357: Inclined layering in the Coire-bheinn Gabbro, SW of summit of Coire-bheinn. [Photograph courtesy of John Faithfull]

9.11.3.3 Ring-dykes

Typically steep-sided and silicic (granite, microgranite, rhyolite), the Centre 2 ring-dykes range from 50–500 m in thickness/width and are best exposed on Beinn Chaisgidle (Figure 9-358). Basic varieties are rare, varying from gabbro to dolerite. Some are composite, with a range of compositions. There are no clear internal contacts.



Figure 9-358: Beinn Chaisgidle, composed of dolerite and gabbro on the lower slopes and various breccias in the summit area. View towards the south from Na Bachdanan, NE of Loch Bà.

Beta version

9.11.3.4 The Glen More Ring-dyke

The Glen More Ring-dyke is a well-known example of a steeply inclined, hybrid intrusion in the Hebridean Igneous Province. It rises nearly 500 m from the Glen More river to the summit of Cruach Choireadail and transitions compositionally from olivine-gabbro to dioritic rocks and then to melanocratic microgranite. Most primary minerals have been replaced by secondary hydrothermal minerals.

This intrusion was pivotal in recognising magmatic differentiation as a process and ring-dyke formation. Bailey *et al.* (1924) and Koomans & Kuenen (1938) proposed *in situ* differentiation by crystal fractionation. Others (Holmes 1936; Fenner 1937) suggested magma mixing between basic and silicic types, a mechanism favoured by Seedhouse (1994).

9.11.3.5 Cone-sheets

Cone-sheets of the Beinn Chaisgidle Centre are mainly basic (basalt and dolerite), inward-dipping at 20°–50° toward a focal point below Beinn Chaisgidle (Figure 9-358). Some are veined by remelted silicic material from intruded ring-dykes. The cone-sheets are usually less than 10 m thick. Complex relationships between silicic ring-dykes and basic cone-sheets are evident throughout Centre 2, especially well exposed in the Allt Molach stream section in Glen More (Figure 9-359).

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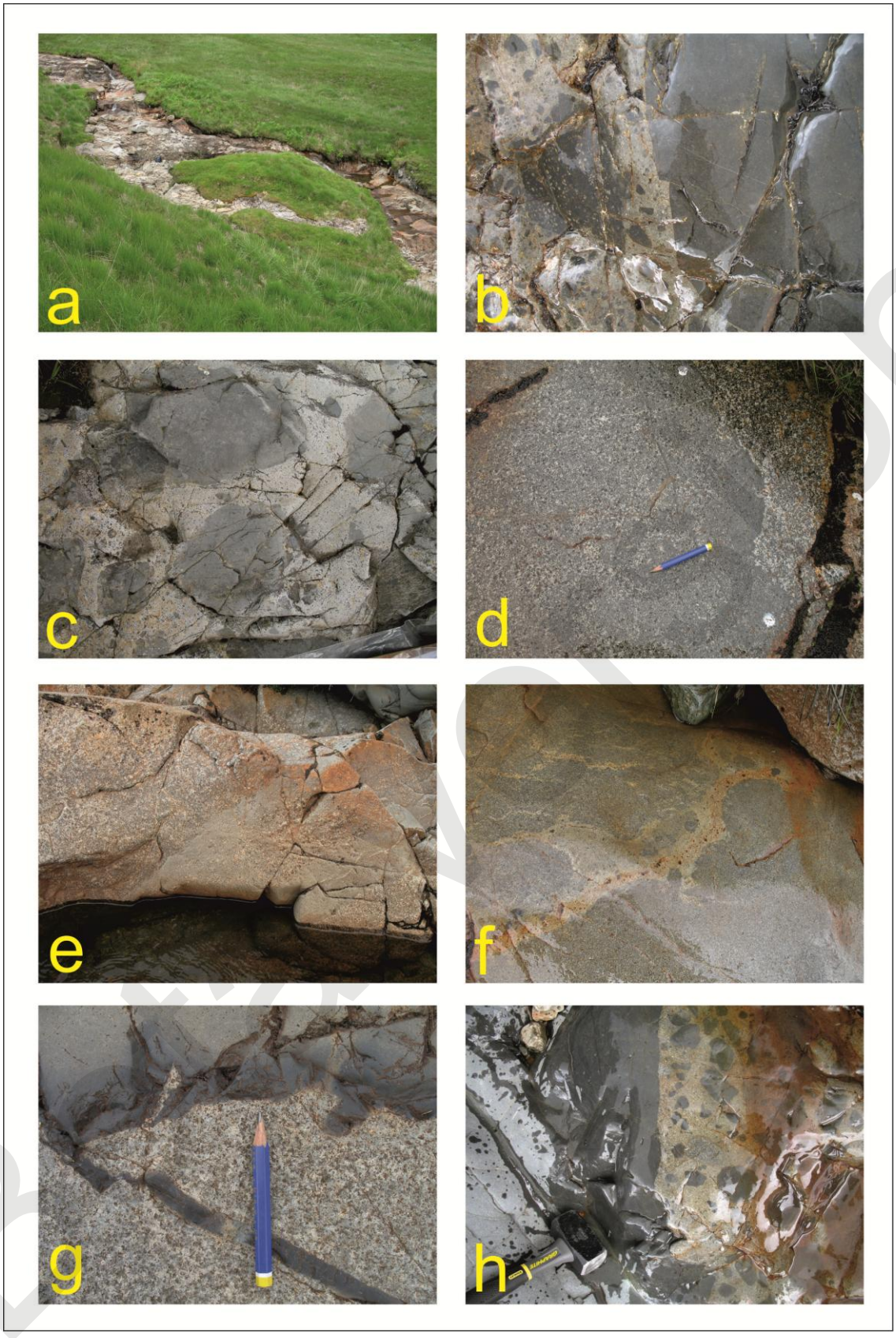


Figure 9-359: Examples of intrusive lithologies and their relationships in the Beinn Chaisgidle Centre in the Allt Molach (stream section) on the north side of Glen More: (a) view of the Allt Molach; (b) basalt intrusion with breccia of basalt fragments in a micro-granite matrix; (c) breccia of basalt fragments in a micro-granite matrix; (d) heterogeneous granite-diorite; (e) heterogeneous granite-diorite; (f) diorite veined by micro-granite; (g) bulbous contact between granite and basalt; (h) basalt intrusion contact with breccia of basalt fragments in a micro-granite matrix.

The final intrusive phase of the Beinn Chaisgidle Centre was the emplacement of quartz-dolerite cone-sheets, also known as the Late Basic Cone-sheets. These were intruded as activity shifted NW to Centre 3, thus forming the youngest intrusive phase of that centre.

9.11.4 Centre 3: The Loch Bà Centre

9.11.4.1 Introduction

Centre 3, also called the Loch Bà Centre, is associated with the formation of the Late Caldera (Figure 9-360).

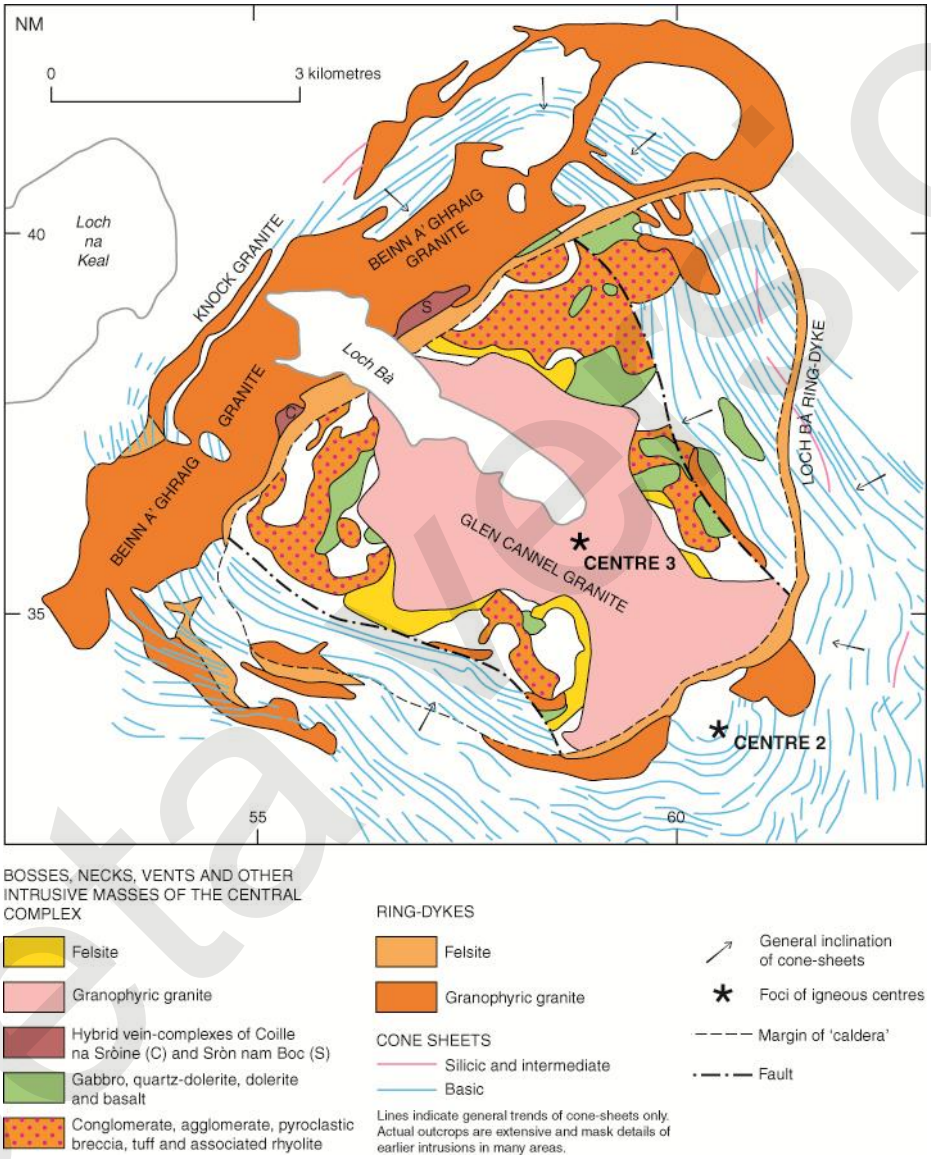


Figure 9-360: Simplified geological map of Centre 3, the Loch Bà Centre (and the Late Caldera), Mull Central Complex (after Emeleus & Bell 2005).

9.11.4.2 The Late Basic Cone-sheets

The Late Basic Cone-sheets represent a transition from Centre 2 to Centre 3. They are cut by and cut through various plutonic intrusions associated with both centres. Around Loch Bà and on Beinn na

Beta version

Duatharach, they are symmetrically arranged along a NW-trending axis (Figure 9-361). Cone-sheet density in some areas is so high that little country-rock remains, implying significant central uplift.



Figure 9-361: Beinn na Duatharach from Na Bachdanan, NE Loch Bà, with obvious inclined cone-sheets.

9.11.4.3 The Glen Cannel Granite

This mildly alkaline granite is the first major silicic intrusion of Centre 3 (Figure 9-362). Dome-shaped with a NW-trending long axis, it is rich in gas cavities (druses) and is mainly preserved within a subsided block inside the Loch Bà Ring-dyke (see below). It intrudes several Late Basic Cone-sheets but is also cut by others beyond the ring-dyke, suggesting overlapping events or multiple intrusions.

It is partially roofed by volcaniclastic breccias, quartz-dolerite, and felsites. Felsites along its margins may be chilled facies, although contacts show sharp intrusive relationships.



Figure 9-362: Glen Cannel from Na Bachdanan, NE Loch Bà.

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9.11.4.4 The Beinn a’ Ghraig and Knock Granites

The Beinn a’ Ghraig Granite, situated outside the Loch Bà Ring-dyke’s NW margin, is petrographically similar to the Glen Cannel Granite, but most likely younger (Figure 9-363; Figure 9-364; Figure 9-365). It cuts cone-sheets but is, itself, only rarely cut by cone-sheets. The Knock Granite is similar in age and composition, forming a steep-sided elongate body separated from the Beinn a’ Ghraig Granite by hornfelsed basaltic lavas. Related granitic, dioritic and hybrid intrusions also exist to the NE of Loch Bà, near Toll Doire, Maol Buidhe, and Killbeg. Despite being invaded by cone-sheets and hornfelsed, the lavas show minimal folding or faulting, suggesting passive emplacement via subsidence and stoping.



Figure 9-363: Beinn a’ Ghraig, composed of the Beinn a’ Ghraig Granite from the summit of Ben More. View towards the NE.

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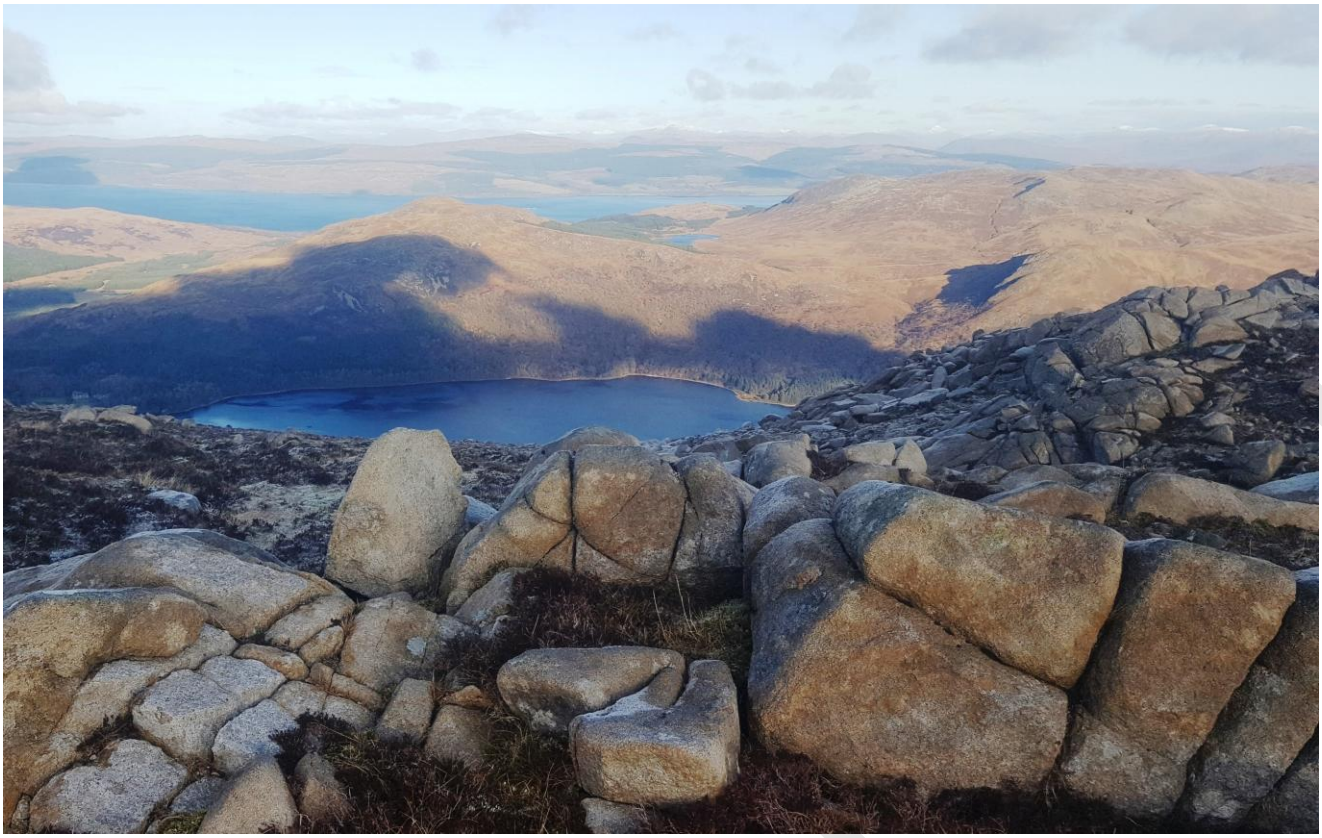


Figure 9-364: The Beinn a' Ghràig Granite, close to the summit of Beinn a' Ghràig. View east towards Loch Bà and, beyond, the Sound of Mull and the Scottish Mainland. [Photograph courtesy of James Westland]



Figure 9-365: Beinn a' Ghraig from the north side of Loch na Keal. View towards the SE.

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9.11.4.5 The Loch Bà Ring-dyke

This is the final major silicic intrusion of the Loch Bà Centre, *ca.* 8 km in diameter with variable width: up to 400 m, but in places represented only by breccia along the ring-fault (Figure 9-366; Figure 9-367; Figure 9-368; Figure 9-369; Figure 9-370). The ring-dyke walls are generally vertical, although parts dip outwards steeply. Locally, it has well developed columnar joints (Figure 9-371).



Figure 9-366: The Loch Bà Ring Dyke from Beinn a'Graig. [Photograph courtesy of Ian Williamson]



Figure 9-367: The Loch Bà Ring-dyke from the NW end of Loch Bà. [Photograph courtesy of James Westland]



Figure 9-368: Columnar-jointed Loch Bà Ring-dyke, viewed NW towards Beinn a' Ghràig and, beyond, Loch na Keal. [Photograph courtesy of James Westland]



Figure 9-369: The Loch Bà Ring-dyke, viewed NW towards Beinn a' Ghràig. [Photograph courtesy of John Faithfull]

B-version



Figure 9-370: Loch Bà Ring-dyke. View towards the NE. [Photograph courtesy of James Westland]



Figure 9-371: Inclined columnar joints in the Loch Bà Ring-dyke. [Photograph courtesy of James Westland]

Unique among Mull's major intrusions, the Loch Bà Ring-dyke is not intruded by cone-sheets, but is cross-cut by the regional NW-SE -trending Mull Main Dyke Swarm (Chapter 7). First described by Bailey *et al.* (1924) and later investigated by Walker & Skelhorn (1966) and Sparks (1988), this hybrid intrusion is recognised as an example of extreme differentiation of tholeiitic basalt magma, together with magma mingling to produce a hybrid rhyolitic body with inclusions of the more basic material (ferrobasalt to

dacite). These inclusions make up less than 10% of the intrusion, often appear glassy, and show rounded or lenticular shapes with ragged ends.

The rhyolite is partially devitrified and displays flow-banding and fiammé, indicating a pyroclastic origin (Sparks 1988); emplacement of the ring-dyke magma involved magma mingling/mixing during explosive eruptions, facilitated by gas brecciation and central subsidence of the block within the ring-fault (Figure 9-372; Figure 9-373; Figure 9-374).

Sparks (1988) proposes that the ring-dyke magma(s) involved extreme closed-system crystal-liquid fractionation, within a deep, internally zoned magma chamber, evolving from basaltic-andesite to rhyolite, capped by a separate rhyolitic layer. A combination of subsidence within the chamber and convective overturn caused rapid mixing of the basaltic and rhyolitic layers, triggering explosive eruptions.



Figure 9-372: Dark, elongate, aligned, basic inclusions within pale rhyolite of the Loch Bà Ring-dyke. Ruler (in cm) for scale. [Photograph courtesy of James Westland]



Figure 9-373: Dark, elongate, aligned, basic inclusions within pale felsite of the Loch Bà Ring-dyke. Ruler (in cm) for scale. [Photograph courtesy of James Westland]



Figure 9-374: Detail of the Loch Bà Ring-dyke, comprising fine-grained, wisp- and bleb-like, basic inclusions within the dominant felsite/rhyolite. Coin ca. 21 mm across.

Troll *et al.* (2021) present geochemical data - major- and trace-elements and Sr–Nd–Pb isotopes - which indicate that the rhyolite ($^{87}Sr/^{86}Sr_i \approx 0.716$) was derived largely from melting of local Moine-type metasedimentary crust ($^{87}Sr/^{86}Sr$ *ca.* 0.717-0.736) (Chapter 2), whereas the mafic inclusions have lower ratios (0.704–0.707), indicating a mantle source.

Other granites within the Loch Bà Centre have intermediate values, suggesting moderate crustal assimilation. Thus, rather than evolving purely by closed-system fractional crystallization (Sparks 1988), Centre 3 magmas incorporated upper crustal melts from Moine rocks during ascent and residence beneath the Mull plateau lavas (Chapter 6) (Troll *et al.* 2021). Features such as drusy cavities and granophyric textures indicate emplacement in the shallow crust (*ca.* 1–2 km depth), within Moine metasedimentary country-rocks. Pb isotope data further confirm Moine metasedimentary contributions, with negligible input from deeper Lewisian Gneiss Complex basement – unlike the earlier intrusive centres of the Mull Central Complex. The more dynamic model proposed by Troll *et al.* (2021) involves assimilation -fractional crystallization (AFC) and active magma–crust interaction, particularly with Moine-type upper crust; basaltic magma inputs repeatedly intruded and hybridized with rhyolitic melt (Figure 9-375). Repeated injections of basaltic magma into a contaminated (with crust) rhyolitic reservoir caused the mingling that produced the hybrid magmas. These interactions would have triggered volcanic activity and caldera collapse, with mingling rarely reaching isotopic equilibrium.

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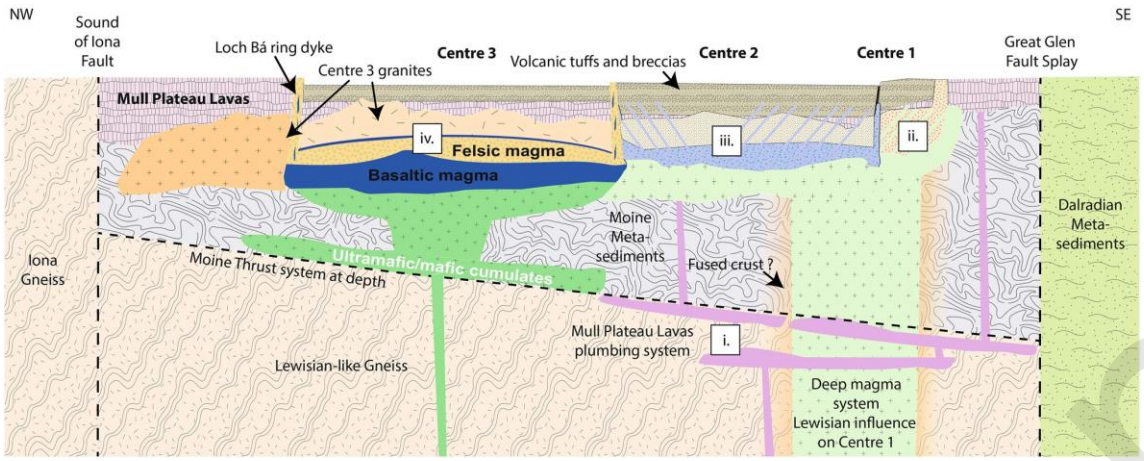


Figure 9-375: Conceptual sketch cross-section of the evolution of the Paleocene Mull Central Complex. The crustal structure is shown schematically and involves the Lewisian-like basement beneath the Moine metasedimentary rocks of Mull. Also schematically represented are the gneisses and metasediments of Iona, located to the SW of Mull and which are uplifted relative to the gneissic basement beneath Mull, therefore representing a possible 'window' into the deeper crustal structure. The Great Glen Fault marks the boundary to Dalradian metasedimentary rocks to the south, which appear to have played no part in the igneous evolution of the Loch Bà Centre. Magma ascent was either via the shielded and or depleted plumbing region of Centre 1, followed by lateral transport to the NW, or via rapid ascent via fissures (represented by dykes) to high levels directly below Loch Bà. All lithologies of the Loch Bà Centre record a dominantly Moine-type contamination signal derived from the local country-rocks at shallow crustal levels. The main magma storage for the Loch Bà Centre was thus confined to the upper portions of the crust, most likely ponding below the thermal and density barrier of the earlier Mull lavas. [Figure courtesy of Valentin Troll]

Interior to the outcrop of the Loch Bà Ring-dyke, on Sròn nam Boc and Na Binneinnean, are various banded rhyolites and breccias (Figure 9-376; Figure 9-377; Figure 9-378). Exposure is poor and the rocks are typically significantly weathered. These lithologies are interpreted by Bailey *et al.* (1924) as the infill of the Loch Bà caldera.



Figure 9-376: Poorly exposed banded rhyolites and coarse breccias on Na Binneinean, from Sròn nam Boc, NE of Loch Bà.

Beta version



Figure 9-377: Rhyolite, NE of Loch Bà. Compass ca. 10 cm long.



Figure 9-378: Bedded breccia, NE of Loch Bà. Compass *ca.* 10 cm long.

9.12 Arran

9.12.1 Introduction

Intrusive Paleocene igneous rocks have a substantial outcrop area on Arran (Figure 9-379) and give rise to significant topographic features: Alpine scenery in the northern part of the island, including the highest point, Goatfell, where the North Arran Granite Pluton has been subjected to Quaternary glaciations; coastal cliffs in the SW, formed of resistant-to-erosion micro-granite sills intruded into softer Triassic strata (Chapter 8); and, inland crags in the SE, formed by dolerite sills. Holy Island in Lamlash Bay is dominated by one of these sills, as is Pladda, off the south coast (Chapter 8). To the south of Arran, the cliff-fringed island of Ailsa Craig is formed from a distinctive riebeckite-bearing granite, famed as being the sole source of curling stones used in Winter Olympic competitions (see below).

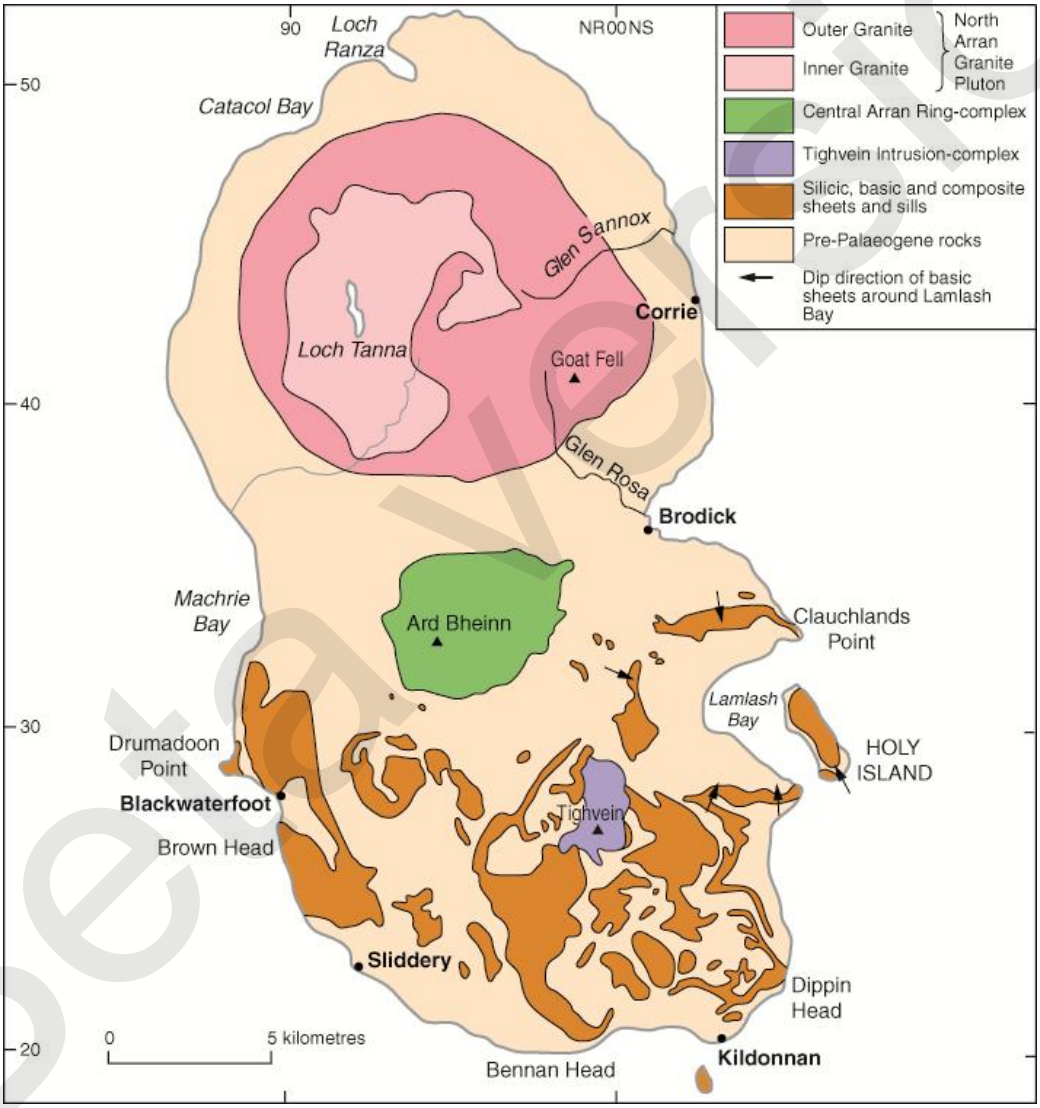


Figure 9-379: Simplified geological map of Arran illustrating the principal Paleocene intrusions (after Emeleus & Bell 2005).

The depths of emplacement of these various intrusions are difficult to determine, although it is generally accepted that it did not exceed *ca*. 3 km. Precise ages of the intrusive events are poorly constrained, with the only reliable age of *ca*. 58.5 Ma for the North Arran Granite Pluton (Chapter 5).

Beta version

Extrusive igneous rocks are limited to the caldera-forming fragmental rocks, part of the Central Arran Ring-complex, forming much of Ard Bheinn in the central part of the island. They are dealt with, below, rather than in Chapter 6.

9.12.2 North Arran Granite Pluton

The North Arran Granite Pluton, with a near-circular (diameter) outcrop of 10-12 km, is a composite intrusion with a coarse-grained Outer Granite and a younger, finer-grained Inner Granite (Figure 9-380; Figure 9-381; Figure 9-382; Figure 9-383; Figure 9-384; Figure 9-385; Figure 9-386; Figure 9-387). The Outer Granite has a steep-sided contact (predominantly) with Dalradian Supergroup psammites and pelites (Chapter 2); west of Corrie, it has a faulted contact with Old Red Sandstone (Devonian) strata (Chapter 2). Locally, the Outer Granite veins the country-rocks. The Outer Granite has a well-developed system of joints, approximately parallel to the present-day land surface, suggestive of their development during unroofing; examples include on Goatfell and on Cioch na h-Oighe. The contact between the Outer and Inner Granites is sharp and is well exposed south of Meall nan Damph and towards the northern end of the A' Chir ridge. The Inner Granite is characteristically drusy; on the west side of Glen Catacol, within stream sections, granite-granite contacts suggest multiple sheeted intrusion.

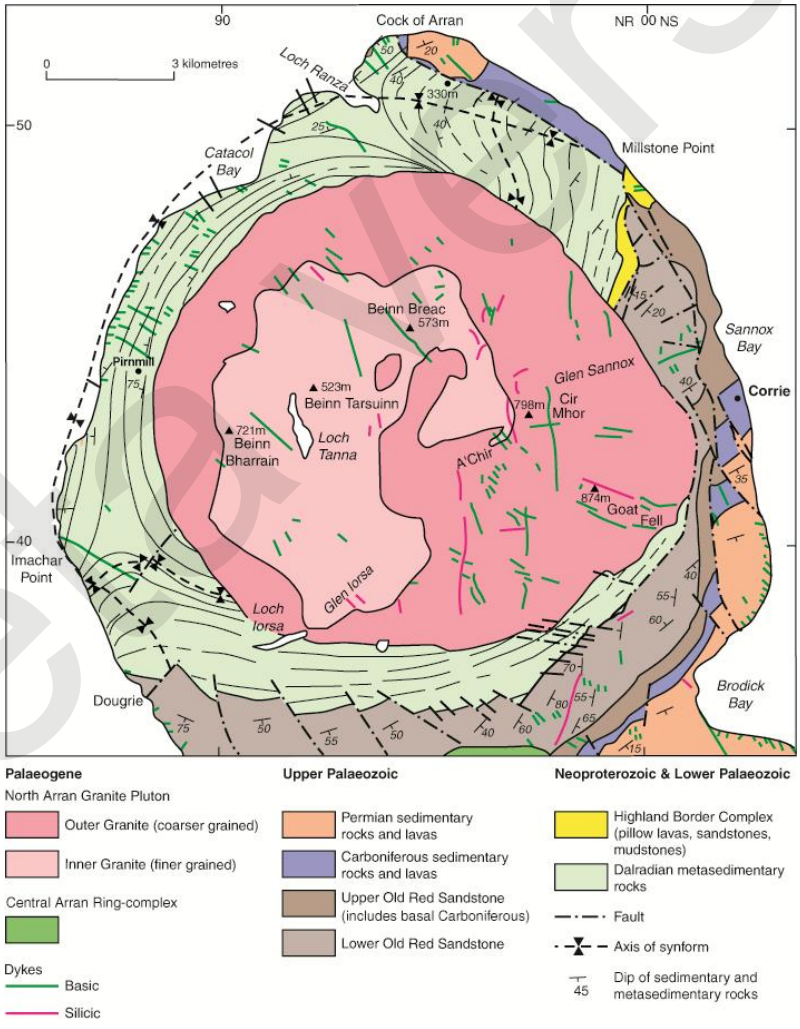


Figure 9-380: Simplified geological map of the North Arran Granite Pluton (after Emeleus & Bell 2005).

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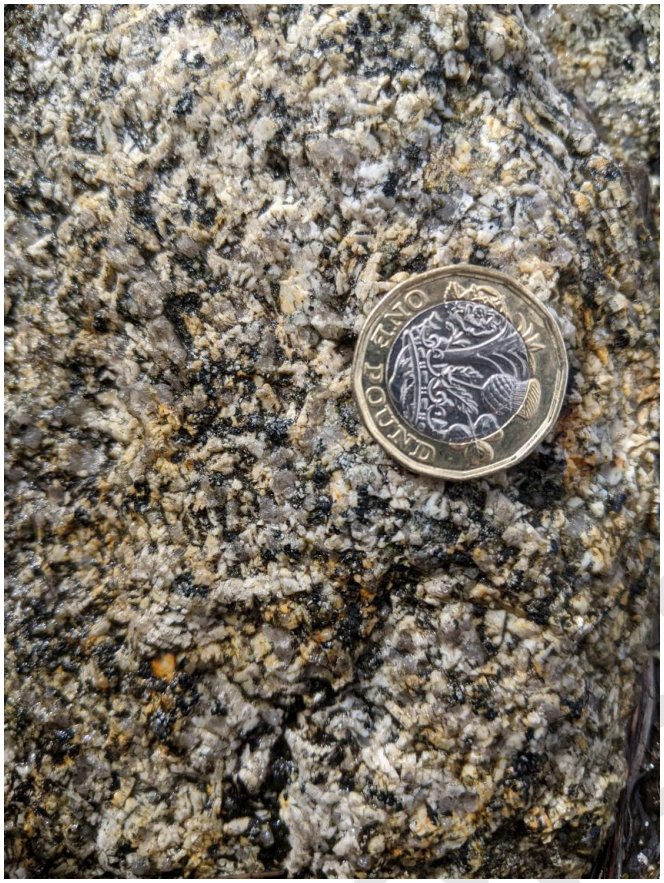


Figure 9-381: Typical (coarse-grained) Outer Granite of the North Arran Granite Pluton, with white-pale brown alkali feldspar, grey quartz and dark biotite. Coin *ca.* 24 mm across.



Figure 9-382: Typical (finer-grained) Inner Granite of the North Arran Granite Pluton, with white-pale brown alkali feldspar, grey quartz and dark biotite. Coin *ca.* 24 mm across.

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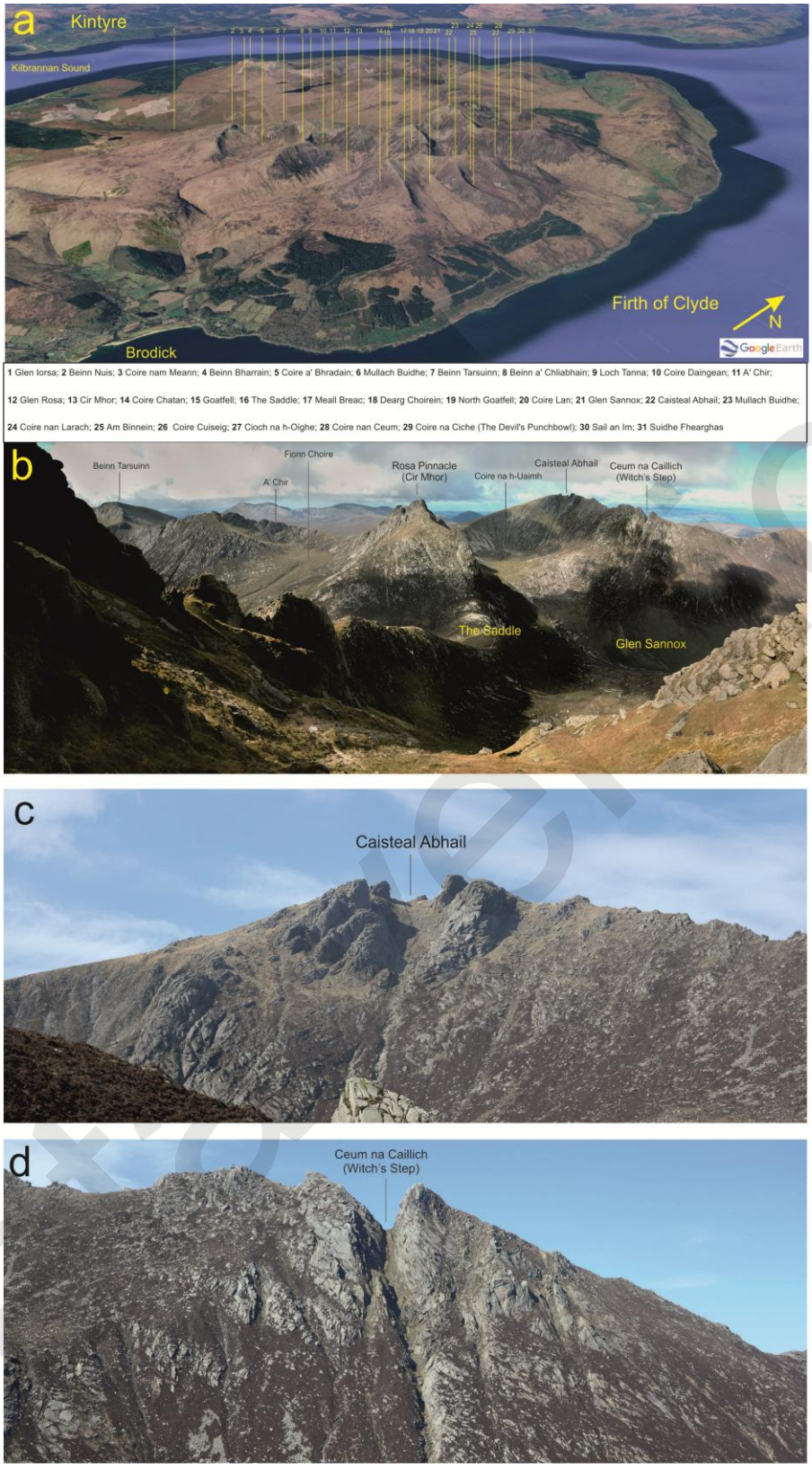


Figure 9-383: (a) Oblique Google Earth© image of north Arran, dominated by the North Arran Granite Pluton, with named summits; (b) granite summits of north Arran, viewed towards the NE from the west side of Goatfell [photograph courtesy of Blair Fraser]; (c) granite summit of Caisteal Abhail, north Arran, viewed towards the NW from The Saddle, northern end of Glen Rosa; and, (d) granite ridge and notch of Ceum na Caillich (Witch's Step), resulting from a more easily eroded dolerite dyke, viewed towards the NW from The Saddle, northern end of Glen Rosa.

Botanical version



Figure 9-384: Oblique aerial view of the heavily glaciated topography of north Arran, formed of the North Arran Granite Pluton, viewed towards the SE from Caisteal Abhail, with obvious block joints. [Photograph courtesy of Richard Cross]

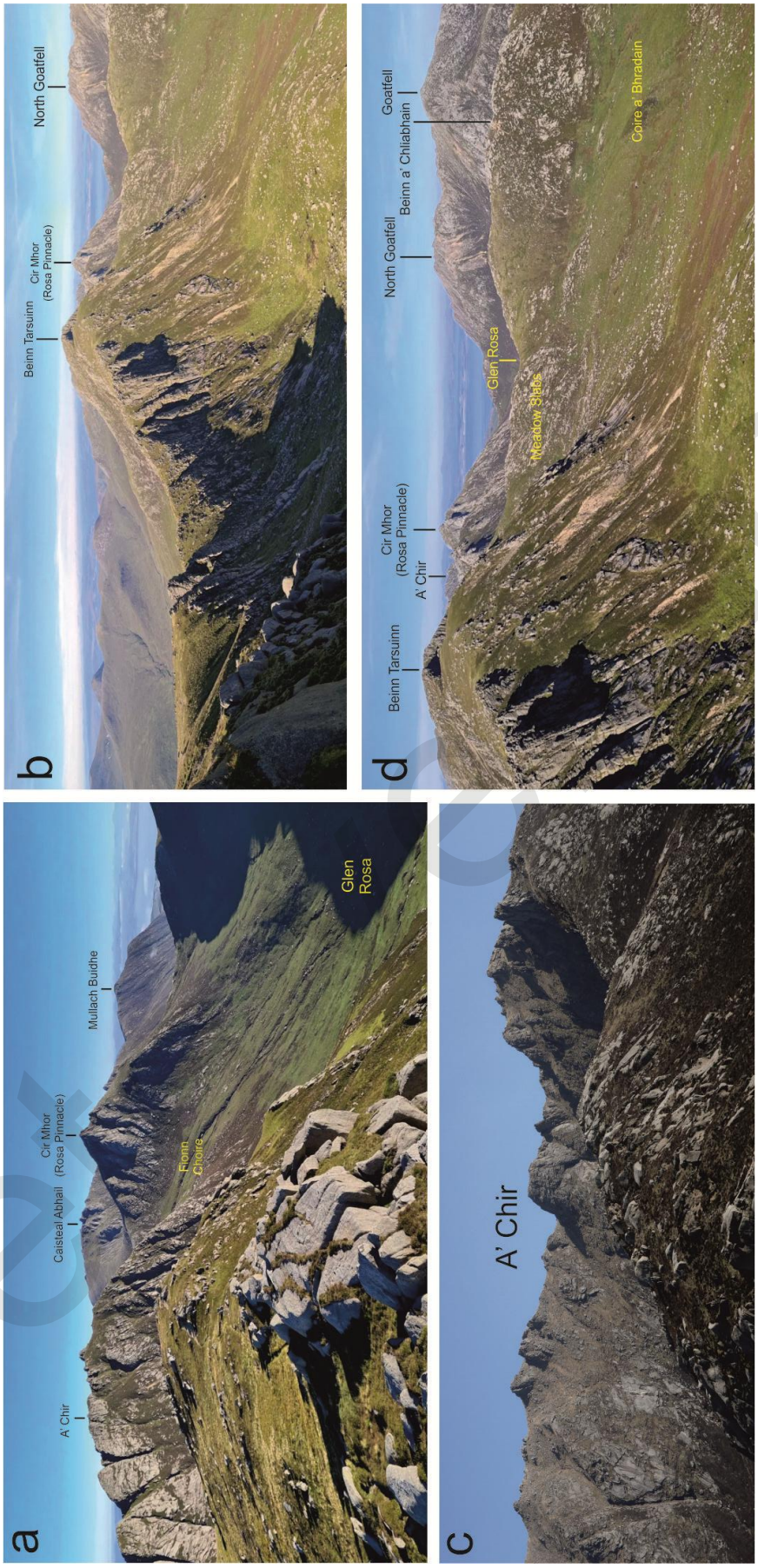


Figure 9-385: Scenic views of the glaciated topography of the North Arran Granite Pluton.

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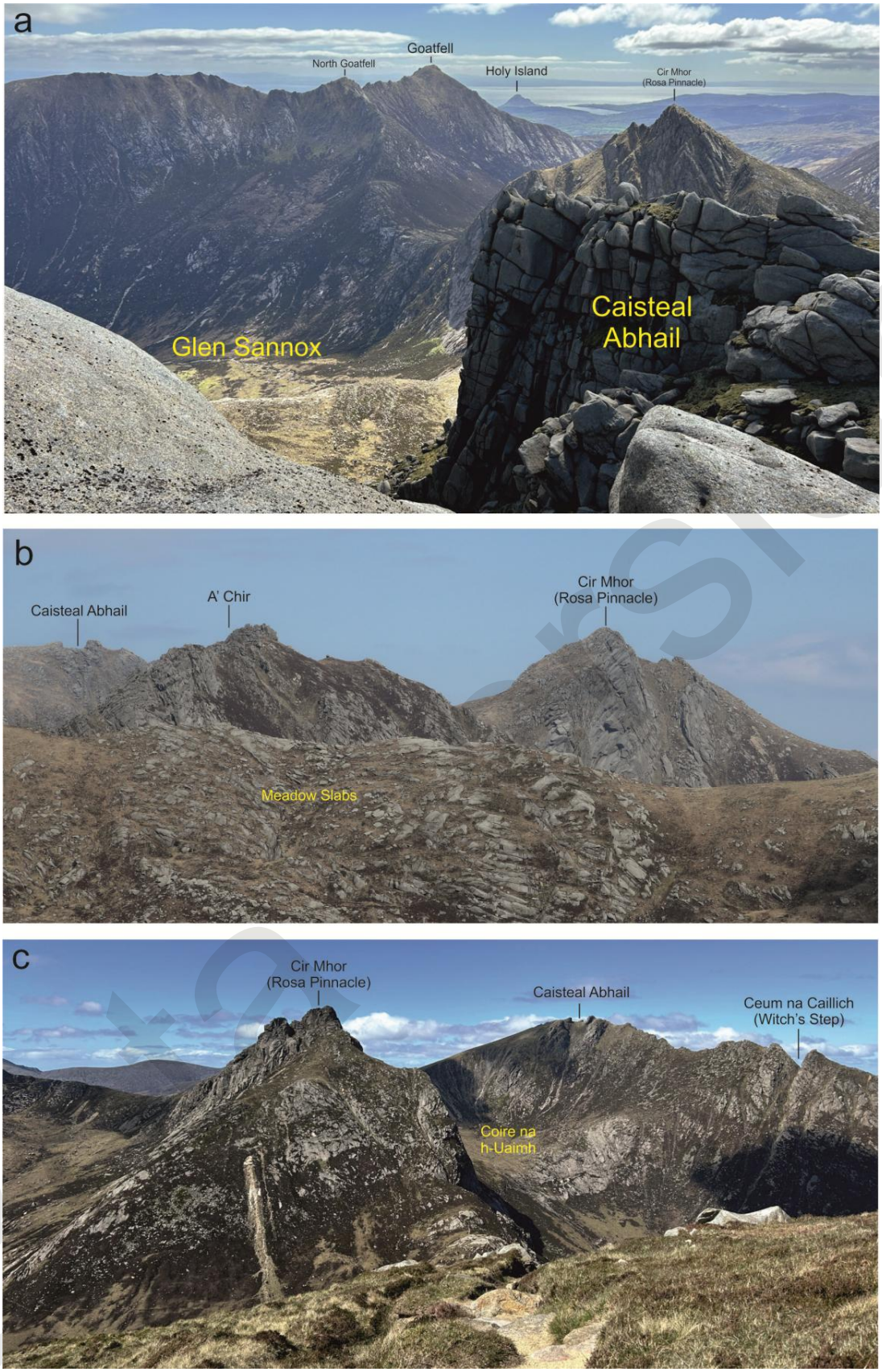


Figure 9-386: Scenic views of the glaciated topography of the North Arran Granite Pluton, north Arran.



Figure 9-387: The 'Bastion' summit of Cioch na h-Oighe, with flat-lying, parallel joints in the NE part of the Outer Granite, North Arran Granite Pluton, SE of Sannox, NE Arran.

Both intrusions are non-porphyritic with biotite as the dominant ferro-magnesian mineral. The entire pluton is normally magnetized, as are the micro-granite and rhyolite sills of SW Arran (see below), suggesting some form of genetic relationship.

A shallow level of intrusion is indicated by the presence of mineral-lined cavities, dominated by quartz, alkali feldspar and mica, together with rare topaz, blue beryl, allanite and zircon. The rare-earth-bearing minerals, fergusonite and gadolinite, are also present (Hyslop *et al.* 1999). Although the outcrop shape and steep-sided contact with the Dalradian Supergroup country-rocks indicates some form of forceful or diapiric emplacement (England 1992), there is no significant mineral alignment of foliation within the marginal zone of the pluton (and indeed throughout both the Outer and Inner Granites).

The country-rock Dalradian Supergroup strata were significantly deformed during emplacement of the granite(s), inferred from the consistent strike of these strata parallel to margin of the pluton (for *ca.* 270° of arc). This feature of the country-rocks is well shown by the outcrop pattern/distribution of distinctive dark pelites (metamorphosed mudstones) on the west and NW side of the pluton. On the north side of the pluton, between Loch Ranza and Catacol, there is a concentric synform, the Catacol Synform. Offshore, between Catacol and Imichar Point, New Red Sandstone (Permo-Trias) strata occur in the core of a concentric synclinal structure affecting Carboniferous and Dalradian rocks. On the east side of the pluton, in the area around Corrie, deformation within the country-rocks is a combination of folding and faulting, involving the reactivation of pre-existing faults. On the west side of the pluton, in the area around Pirnmill, small reverse faults within the country-rock Dalradian Supergroup strata are inclined towards the pluton. South and SE of the pluton, doming has affected Old Red Sandstone (Devonian), Carboniferous and New Red Sandstone (Permo-Trias) strata, for example in Glen Cloy, west of Brodick.

Beta version

The thermal aureole extends out for several hundreds of metres, although the mineralogical features are not easily recognized without detailed petrographic analysis. Xenoliths of these hornfelsed materials occur locally, most commonly close to the outer contact.

9.12.3 Central Arran Ring-complex

The variably exposed Central Arran Ring-complex (CARC) is a complicated suite of extrusive (effusive and pyroclastic), intrusive and sedimentary rocks, exposed on Ard Bheinn and the surrounding area, south of The String road (Figure 9-388) (Gunn *et al.* 1903; Tyrell 1928; King 1955; Gooday *et al.* 2018). The total area is estimated at *ca.* 20 km^2. The country-rocks are Old Red Sandstone (Devonian), Carboniferous and New Red Sandstone (Permian) sedimentary rocks, with contacts with the various units of the ring-complex being faults. These country-rocks have a domed geometry with respect to the North Arran Granite Pluton (see above), suggesting that the ring-complex is younger. The presence of mega-blocks of Jurassic and Cretaceous strata (Chapter 3) indicate an original country-rock cover, shattered during caldera formation and preserved due to the central subsidence (caldera-forming) events. The most conspicuous mega-block lithology is Cretaceous limestone (chalk), with examples on the western slopes of Binnein na h-Uaimh and on Creag Dubh; the weathering and erosion of the former give rise to a solution hollow, the informally named Pigeon Cave. Fragments of basalt suggest the possibility of a cover of Paleocene lavas (Chapter 6), common elsewhere within the Hebridean Igneous Province, but not on Arran. The intrusive igneous rocks are interpreted as partial ring-dykes, emplaced during the caldera-forming events.



Figure 9-388: Ard Bheinn, east of the Shiskine Valley, SW Arran.

King (1955) and Gooday *et al.* (2018) interpret the extrusive igneous rocks as belonging to a caldera, with the latter recognizing only pyroclastic lithologies. The details set out below are mainly from that of Gooday *et al.* (2018) (Figure 9-389; Figure 9-390). Hydrothermal alteration is limited, and permits the interpretation of some original textures, critical in the identification of these pyroclastic rocks.

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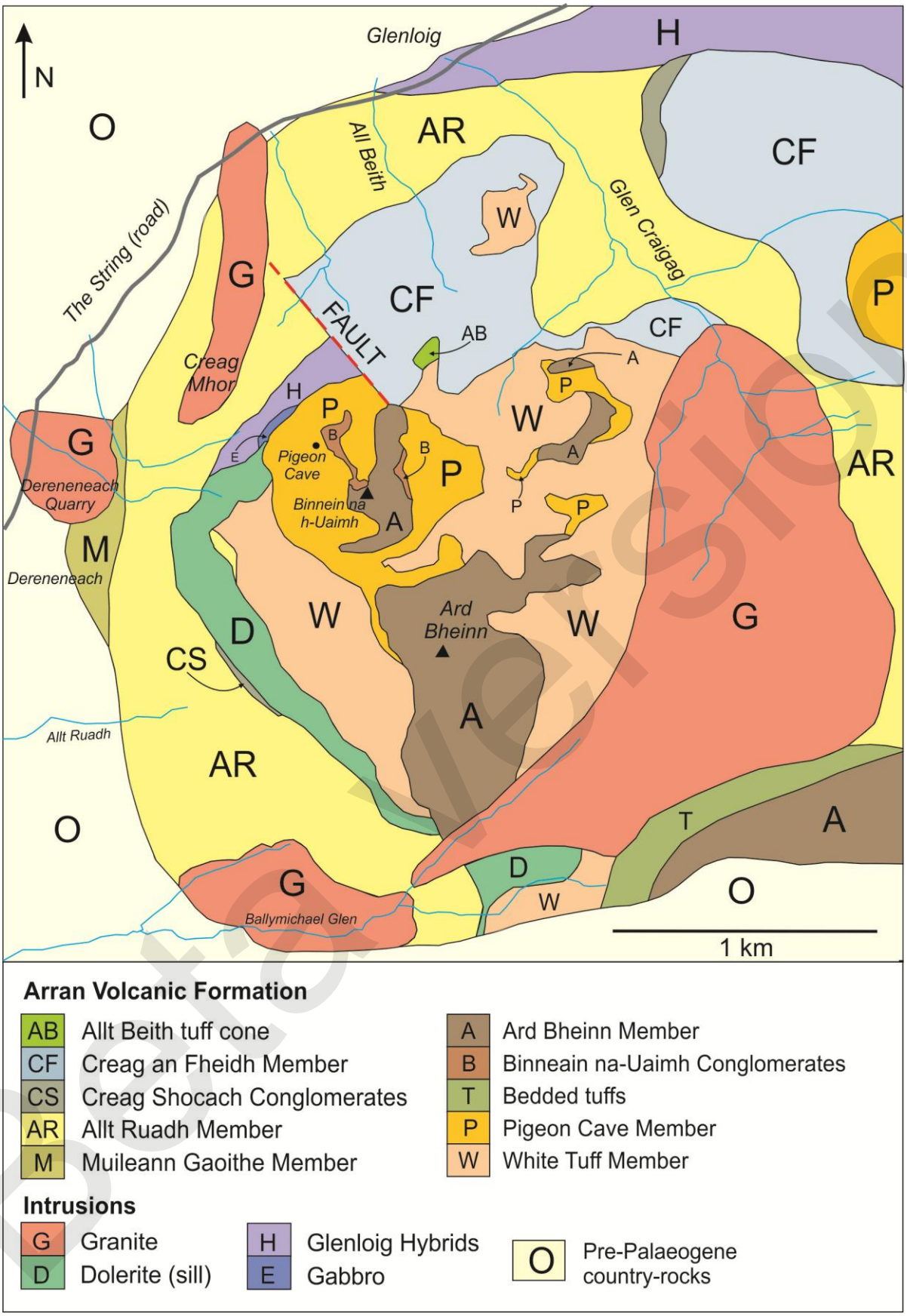


Figure 9-389: Simplified geological map of the Central Arran Ring-complex (after Gooday *et al.* 2018).

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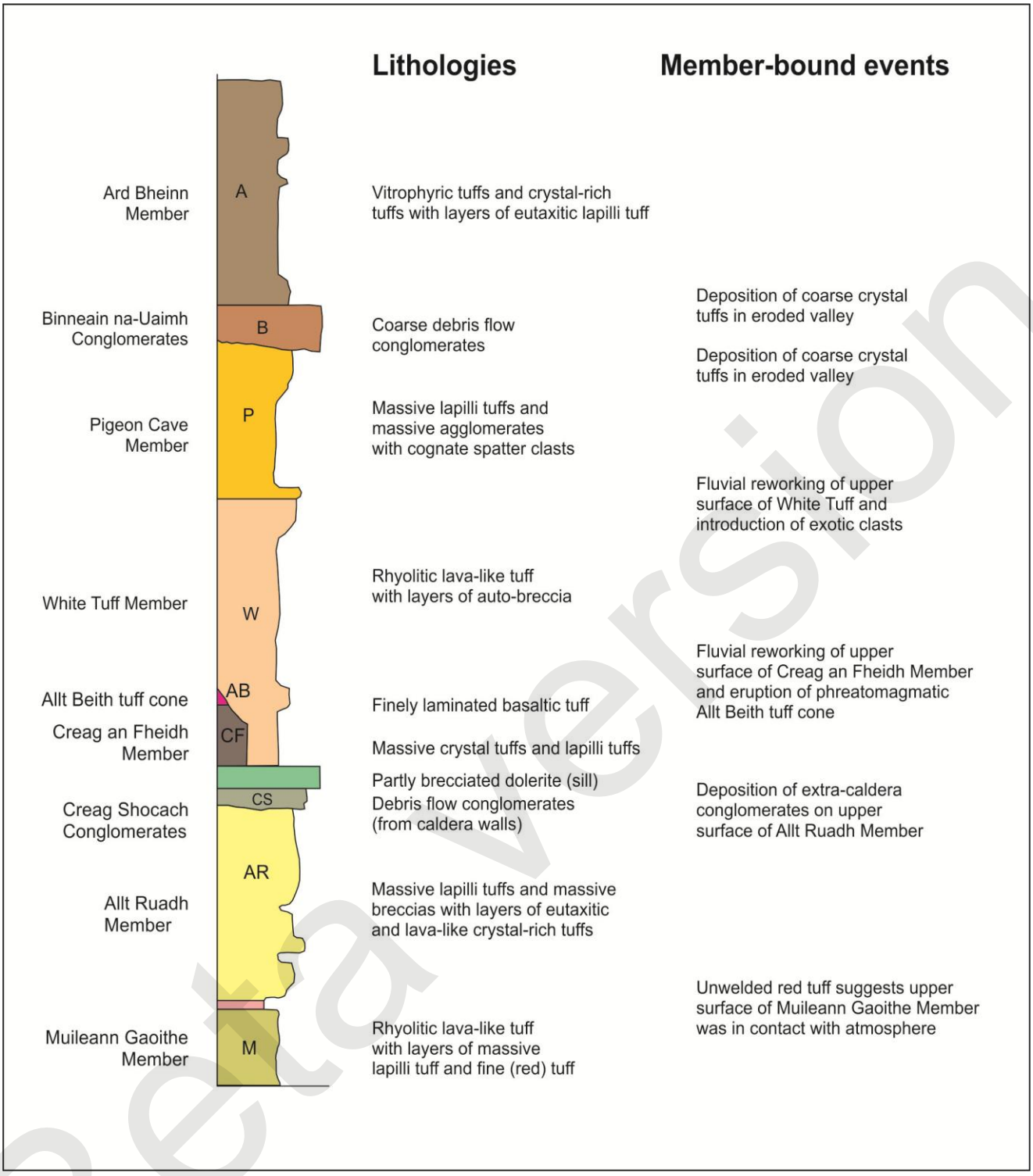


Figure 9-390: Generalised stratigraphic log of the volcanic sequence within the Central Arran Ring-complex. Vertical thicknesses not to scale. (after Gooday *et al*. 2018).

Gooday *et al*. (2018) interpret the fragmental rocks within the ring-complex as proximal (intra-caldera) pyroclastic rocks, mainly ignimbrites, with interbedded sedimentary units. Minor unconformities are recognized. The best exposures are in the Ard Bheinn – Binnein na h-Uaimg area. Exposures occur over a vertical range of *ca*. 400 m, providing a poorly constrained indication of the overall thickness of the caldera fill.

Beta version

The oldest unit is a rhyolitic lava-like tuff, the product of a low-fountaining pyroclastic eruption. This was followed by highly explosive Plinian eruptions that resulted in a thick sequence of massive (unstratified) lapilli-tuffs. Caldera collapse followed, gradual and incremental, together with the erosion of the newly formed caldera walls. A subsequent sequence of lava-like tuff, eutaxitic tuff, spatter-rich agglomerates and heterogeneous tuffs was deposited. Periods of volcanic quiescence and erosion are indicated by interbedded sedimentary units, mainly conglomerates. Standing water is suggested by phreatomagmatic tuff deposition.

Much of the caldera-fill sequence appears to have maintained its original horizontal attitude, albeit poorly constrained, suggesting piston-like subsidence, with the caldera floor bounded by an (unexposed) steeply inclined ring fault, inferred by the juxtaposition of the caldera fill and the pre-Paleocene country-rocks (Figure 9-391). Intra-caldera faults are largely absent. A subsequent resurgence of pyroclastic activity may have caused doming of the caldera floor and the radial distribution of younger ignimbrites and sedimentary units.

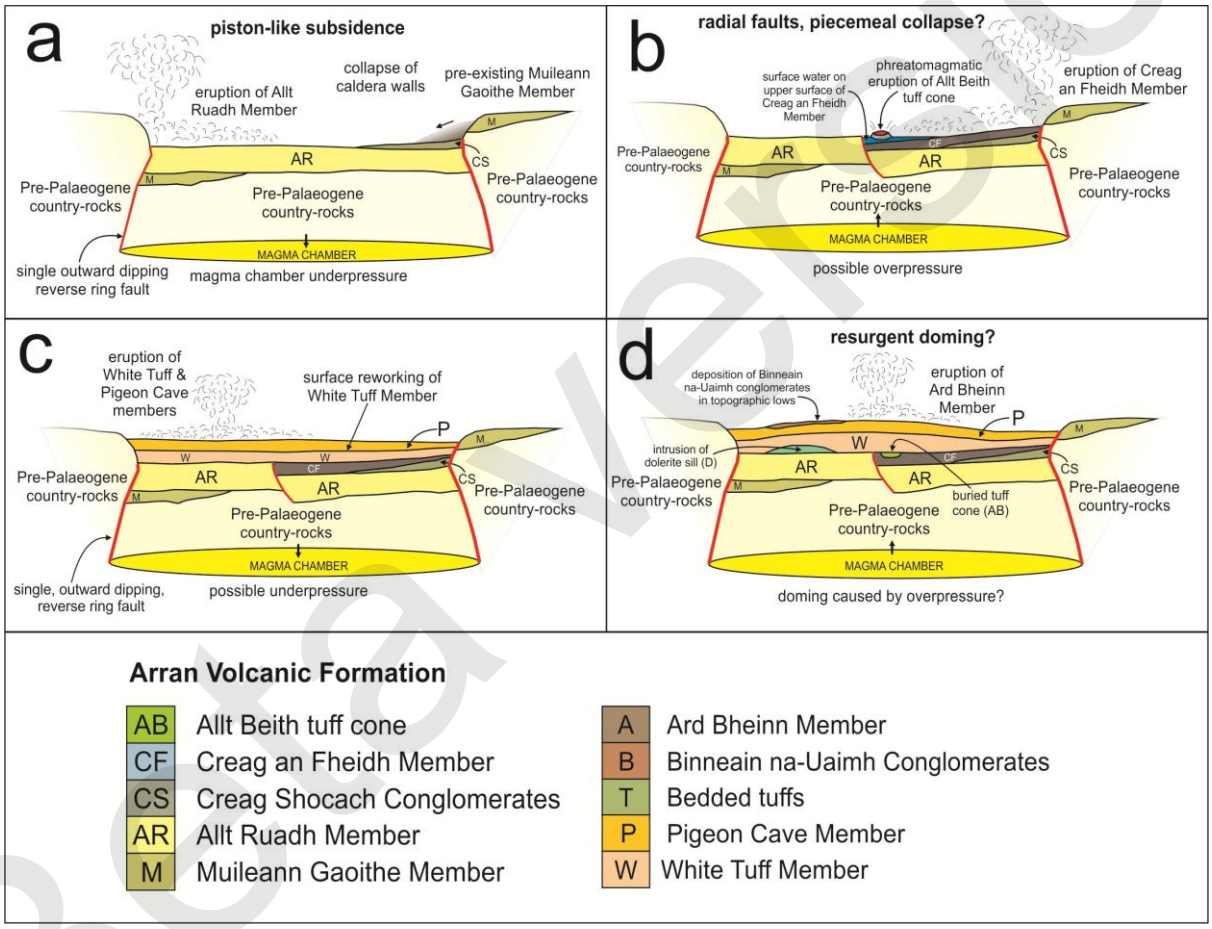


Figure 9-391: A sequence of chronological, generalized cross-sections through the Arran Volcanic Formation of the Central Arran Ring-complex (after Gooday *et al.* 2018).

Gooday *et al.* (2018) interpret the associated intrusive rocks, many of which are of hybrid character, resulting from magma mingling events, as being pre-caldera. Within this suite of intrusive rocks, referred to as the Glenloig Hybrids, are basaltic-andesite, dacite and rhyolite (granite) variants.

King (1955) produced a highly schematic, though informative, cross-section through the Central Arran Ring-complex, prior to erosion. The section is only approximately to scale, but the main cone may be regarded as representing Ard Bheinn (King 1955) (Figure 9-392).

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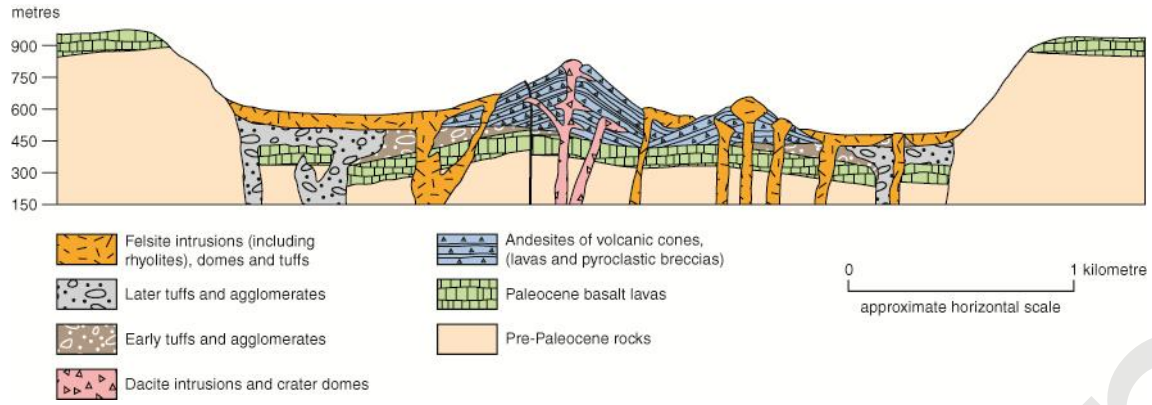


Figure 9-392: King's (1955) interpretation of the volcanic sequence within the Central Arran Ring-complex.

9.13 Ailsa Craig

Ailsa Craig is a spectacular, conical island in the Firth of Clyde *ca*. 20 km south of Arran (Figure 9-393; Figure 9-394; Figure 9-395; Figure 9-396). It is formed by a boss of peralkaline microgranite intruded into Triassic rocks (not exposed on the island). The microgranite is characterised by riebeckitic arfvedsonite and Zr-rich aegirine (Harding 1983; Harrison *et al*. 1987); aenigmatite also occurs (Howie & Walsh 1981). Rare basaltic dykes intrude the granite. This distinctive granite is a widespread glacial marker southwards, on either side of the Irish Sea. It has traditionally been a favoured lithology for the manufacture of curling stones (Chapter 14).



Figure 9-393: South side of Ailsa Craig, illustrating the vertical columnar joints throughout much of the outcrop. Summit 340 m OD.

Beta version



Figure 9-394: SW side of Ailsa Craig, illustrating the vertical columnar joints throughout much of the outcrop. Summit 340 m OD.



Figure 9-395: Detail of the vertical columnar joints throughout much of the outcrop of the Ailsa Craig Granite.

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Figure 9-396: A rare basaltic dyke intruded into the Ailsa Craig Granite.

9.14 Rockall

This body of peralkaline granite forms a precipitous islet, *ca*. 20 m high and 30 m across, in the Atlantic Ocean about 250 km west of St Kilda (Harrison 1975) (Figure 9-397). The nearby micro-gabbro of Helen's Reef is thought to be part of the same intrusive centre, and a variety of igneous rocks have been recorded from the adjacent seabed (Morton & Taylor 1991). Gneisses, which have also been recovered from the seabed, form the country-rock and are Early Proterozoic in age. The granite is unusually rich in aegirine and riebeckite (13 to 27 per cent), and there is a particularly high concentration of ferromagnesian minerals (up to 68 per cent) in the variety 'rockallite', which forms vein-like segregations in the granite. Accessory minerals include elpidite, rare monazite and the barium-zirconium silicate bazarite (first described from Rockall). Leucophosphite occurs as a late-stage replacement mineral, formed by reaction between phosphate-rich fluids derived from sea-bird droppings and the potassium feldspars and ferromagnesian minerals of the granite.

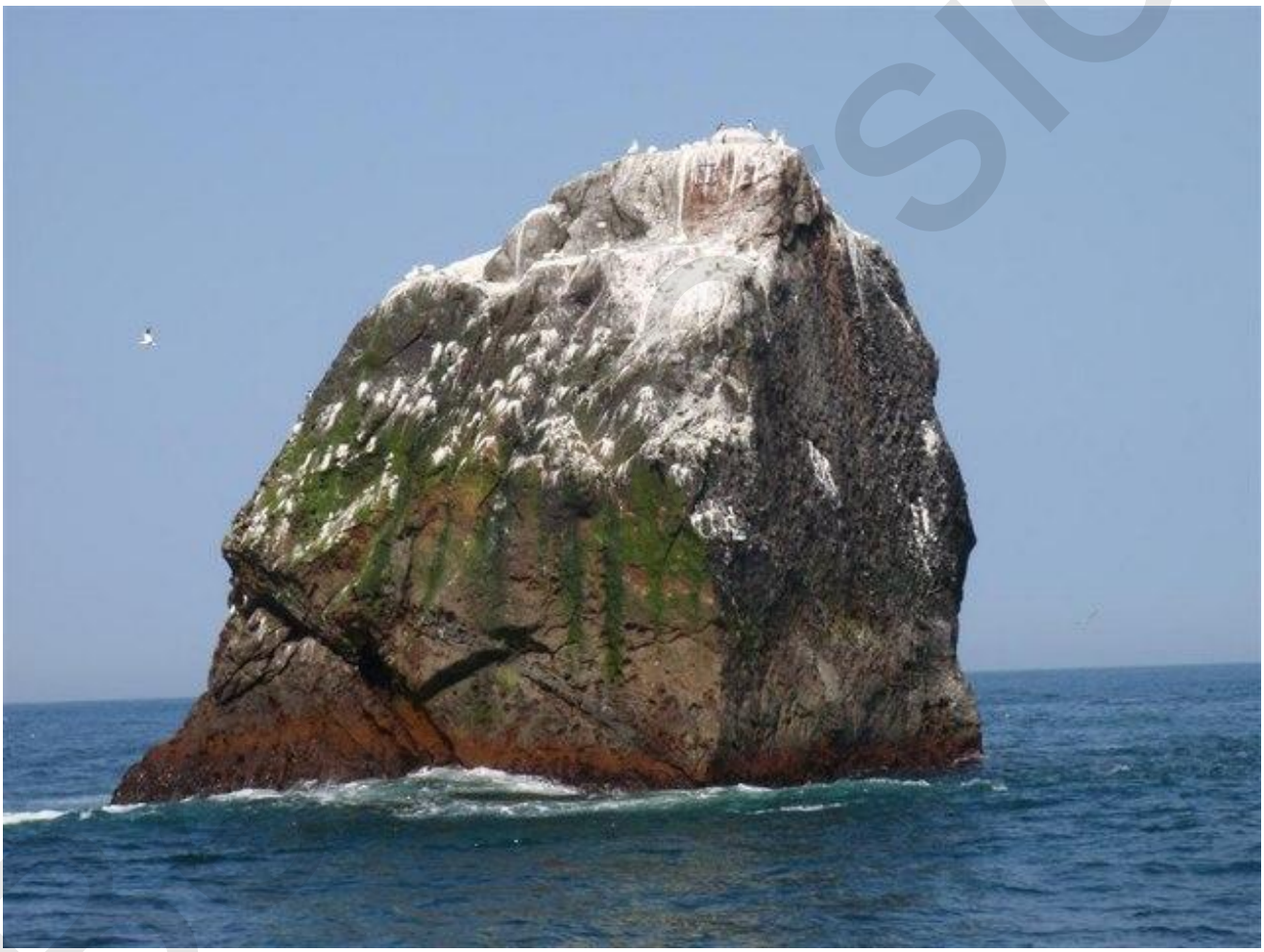


Figure 9-397: Rockall, composed of granite, the only exposure of a larger central complex, ca. 250 km west of St Kilda. [Photograph courtesy of Andy Strangeway, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=7686480]

9.15 Blackstones Bank

The submarine Blackstones Bank Central Complex lies within the Hebridean area (Figure 9-398), *ca*. 30 km SSW of Tiree, and was first located by seismic, magnetic and gravity surveys (McQuillin *et al*. 1975;

Fyfe *et al.* 1993). The age of the complex is most likely Paleocene. It has a rugged topography, and the shallow depths of some parts have allowed extensive sampling by scuba diving (Durant *et al.* 1976, 1982) and the construction of a geological sketch map (Fyfe *et al.* 1993). Most of the accessible parts are of gabbro, commonly exhibiting cumulate textures. Granophyric granite, microgranite and tuffisite samples have also been recovered, together with calc-silicate hornfels. The bank is the site of both a large positive Bouguer gravity anomaly and a major magnetic anomaly. It is therefore likely that basic and ultrabasic rocks make up the bulk of the central complex, with the calc-silicate hornfels formed from the thermal alteration of the Mesozoic sedimentary rocks which it intrudes. From a geochemical study of the centre, it is inferred that the magmas interacted with crustal rocks, similar to those of Proterozoic age exposed in western Islay, implying that such crust extends to the west of the Great Glen Fault (Dickin & Durant 2002).

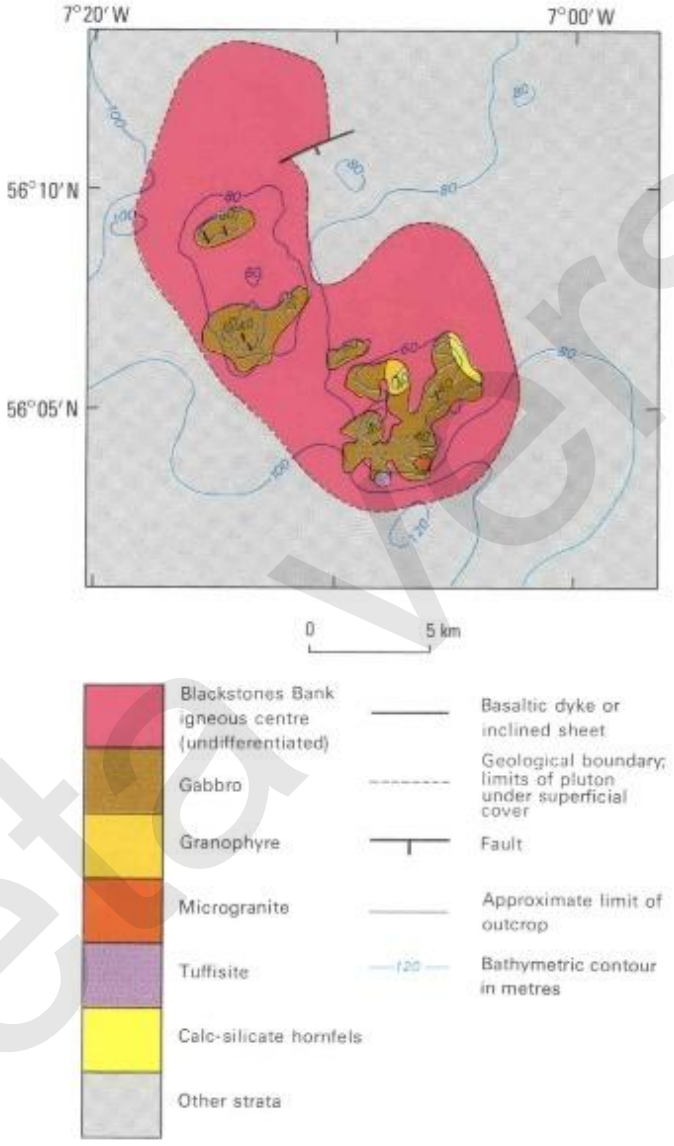


Figure 9-398: Outcrop map of the Blackstones Bank Central Complex (after Fyfe *et al.* 1993).

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10 Magmas

10.1 Introduction

The volcanic and subvolcanic rocks of the HIP have, over the past 150 years, acted as a testing ground for virtually all models and theories of magmatic processes. In early landmark studies, Harker (1904) identified fractionation trends within the Skye Lava Field and magma mixing/interaction and crystal fractionation processes within the intrusive rocks of the Skye Central Complex. Bailey *et al.* (1924) recognised and developed the concepts of magma-types and magma series. Many more recent investigations have attempted to quantify a wide range of magmatic processes. Here, it is only possible to summarise some of the important historical developments and current state of knowledge.

10.2 Magma-types and trends

The concepts of magma-types and magma series (or evolutionary trends) was developed by Bailey *et al.* (1924) from their study of the Mull Lava Field and the Mull Central Complex. Within their so-called Normal Mull Magma Series they identified the Plateau Magma-type, the Non-Porphyritic Magma-type, the Intermediate to Sub-acid Magma-type and the Acid Magma-type. The Plateau Magma-type, of alkali olivine-basalt affinity, was attributed a parental status relative to the derivative status (by fractional crystallization) of the others. Bailey *et al.* (1924) identified the problem of such a silica-undersaturated magma producing the rhyolitic rocks of the Acid Magma-type and invoked that the assimilation of sialic crust must have been involved. Bowen (1928) essentially agreed with this model but proposed that efficient removal of early-precipitated olivine was the dominant process for the generation of rhyolite/granite magma. Kennedy (1930) suggested a totally opposing model, whereby the Non-Porphyritic Magma-type, of tholeiitic basalt affinity, was parental to the (therefore derivative) Plateau Magma-type. Kennedy (1933) subsequently revised his ideas and suggested that both magma-types, renamed olivine basalt (later alkali olivine basalt of Tilley (1950) and nepheline-normative) and tholeiitic basalt (hypersthene-normative) were of parental status. From the experimental studies of Yoder & Tilley (1962) it was evident that under low-pressure conditions, one type could not yield the other type by crystal-liquid fractionation.

Subsequent geochemical studies of magmatic processes within the HIP commenced with the classic investigation of the major-element compositions of Skye lavas by Thompson *et al.* (1972). This study demonstrated that although the Skye lavas, which they assigned to a Skye Main Lava Series (SMLS), were petrographically of alkali olivine basalt type, in detail they varied from nepheline- to hypersthene-normative in composition. Nepheline-normative lavas have a typical alkali olivine basalt major-element composition, but with many of the minor- and trace-element concentrations more typical of tholeiitic basalt. The fractionation trend of the SMLS can be successfully depicted on a modified 'Basalt Tetrahedron' (from Yoder & Tilley 1962), which clearly illustrates how the least evolved members straddle the thermal barrier defined by the 'Critical Plane of Silica Undersaturation' (the olivine-diopside join in Figure 10-1). This operates at pressures less than *ca.* 8 kbar (0.8 GPa, *ca.* 30 km depth). These observations indicated that the major-element compositions of the SMLS were imparted at depth, where the thermal barrier does not operate. Experimental studies (Thompson 1974) indicate that the most primitive compositions developed at pressures of up to 17 kbar. Relatively fast eruption rates are implied, with no opportunity for re-equilibration during ascent.

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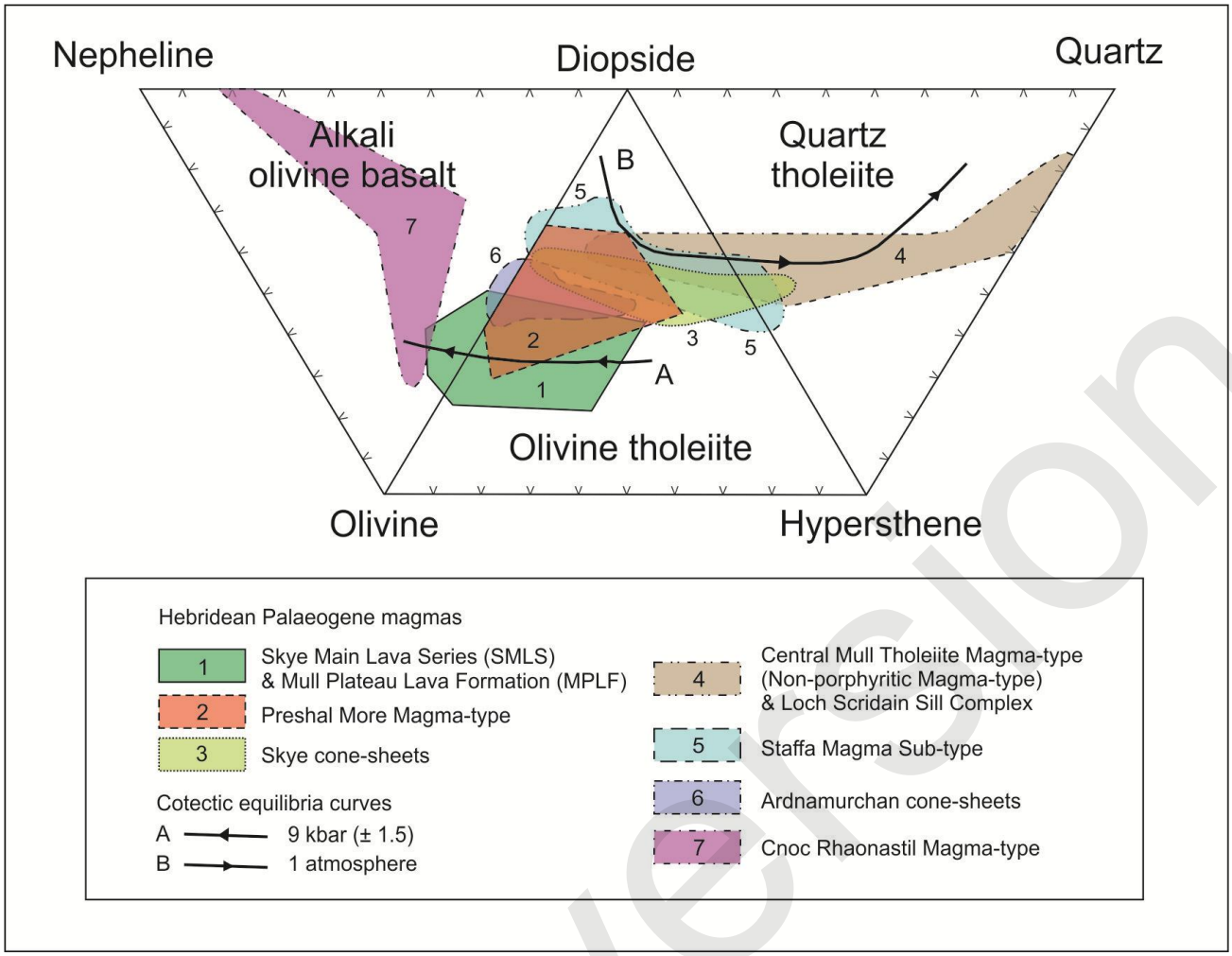


Figure 10-1: Normative CIPW plot showing the compositional fields of Hebridean Paleocene magma-types and 1 atmosphere and 9 kbar (anhydrous) cotectic curves for the equilibria: olivine + plagioclase + clinopyroxene + natural basic/basaltic liquids (after Thompson 1982). See main text for discussion and references.

Two evolutionary trends then developed: (i) the Benmoreite Trend: alkali olivine basalt-hawaiite-mugearite-benmoreite; and, (ii) the Trachyte Trend: alkali olivine-basalt-Si-rich and Fe-poor intermediates-trachyte (Figure 10-2). The Benmoreite Trend developed deep within the crust under high pressures, whereas the Trachyte Trend is the result of low-pressure crystal-liquid fractionation. The major-element signatures of lavas of the Skye Lava Field also occur within the Mull lavas: the Mull Plateau Lava Formation (MPLF) (formerly Mull Plateau Group, MPG; Beckinsale *et al.* 1978; Morrison *et al.* 1980; Kerr 1995a; Kerr *et al.* 1999) and a similar model is implied.

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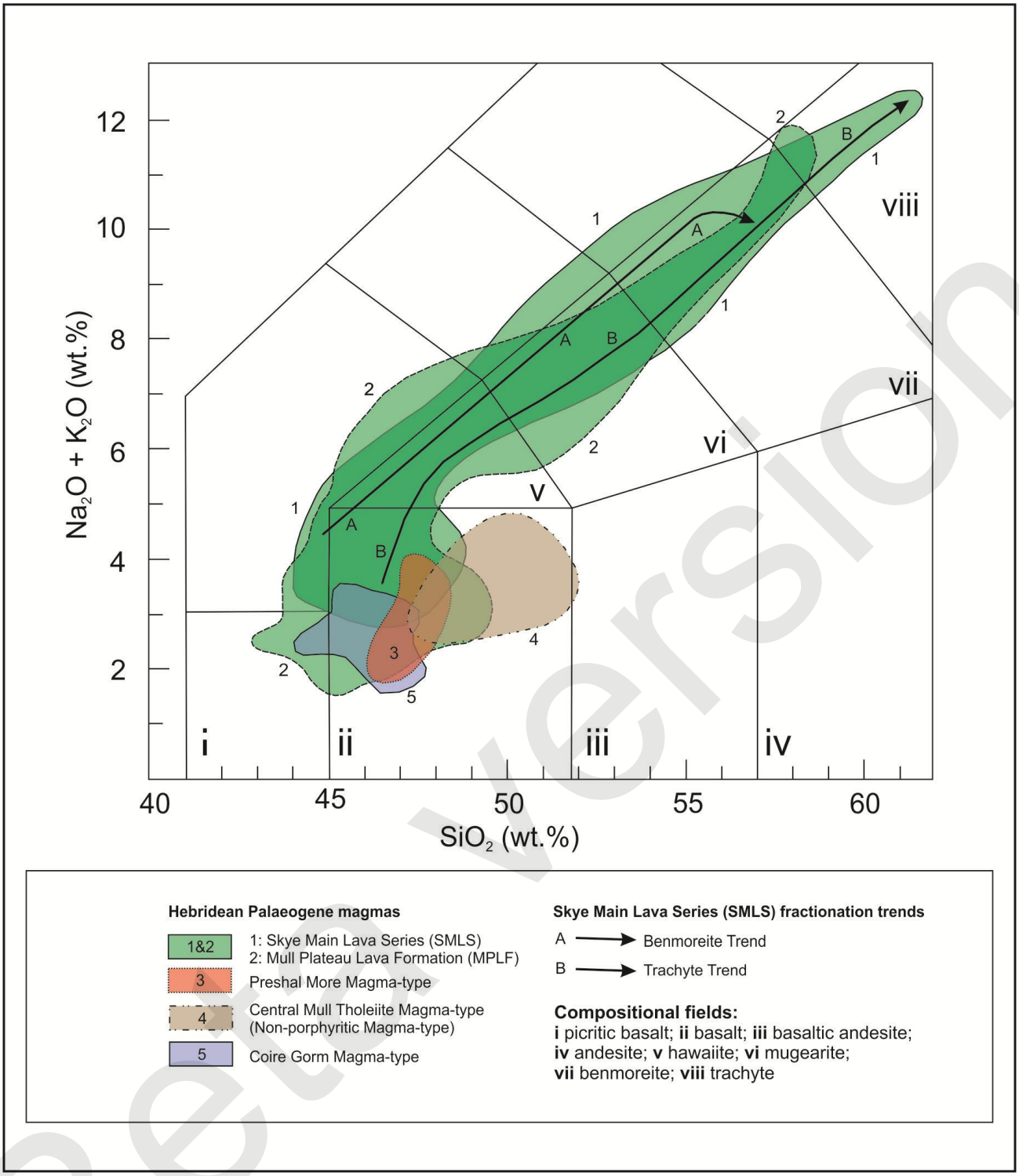


Figure 10-2: Plot of total alkalis ($Na_2O + K_2O$) against silica (SiO_2) illustrating Hebridean Paleocene magma-types and trends superimposed upon the compositional fields of alkali and tholeiitic basalts and their related differentiates. See main text for discussion and references.

Beta version

The tholeiitic basalt lavas within the Staffa Lava Formation of the Mull Lava Field have a complex origin, involving fractional crystallization and significant crustal contamination of transitional magmas of the MPLG (Thompson *et al.* 1986; Kerr 1998). The distinctive Preshal More lava at the top of the preserved sequence on Skye, together with dykes from the axial portion of the Skye Dyke swarm (Esson *et al.* 1975; Mattey *et al.* 1977) and cone-sheets of the Cuillin Intrusive Centre (Bell *et al.* 1994), differ from the Mull tholeiitic basalt lavas, and have distinctive high Ca, and low K, Ti and P compositions, akin to Mid Ocean Ridge-type basalts (MORB).

The primary nature of the basic magmas was imparted by variable degrees of partial melting of a heterogeneous Mantle. The SMLS and MPLF, together with the Little Minch Sill-complex (Gibson 1990) and non-axial dykes of the main swarms (Mattey *et al.* 1977), were derived from a Ca-poor basalt. The tholeiitic basalt magmas (i.e. Non-Porphyritic Magma-Type) are richer in Si and Ca, but poorer in Fe, Ti and P. However, given that there is significant compositional overlap between the two magma-types, it is important to note that the distinction between them can only be made for the least evolved compositions.

10.3 Contamination mechanisms

Contamination mechanisms and their geochemical signatures Interaction between Mantle-derived magmas and continental crust causes detectable modifications of the trace-element and isotope geochemistry (Sr, Nd and Pb) of the magmas (Figure 10-3; Figure 10-4). Contamination is possible due to the exothermic nature of (fractional) crystallization, leading to the partial melting of wall-rocks. The timing of contamination can be assessed: before, during or after fractional crystallization. Of particular interest, assimilation during fractional crystallization (AFC) can be recognized by certain geochemical correlations. Within the Hebridean area, the likely crustal contaminants are lower crustal (granulite-facies) Lewisian gneiss, upper crustal (amphibolite-facies) Lewisian gneiss, Moine pelites and psammites, Dalradian pelites, and Torridonian feldspathic sandstones and siltstones.

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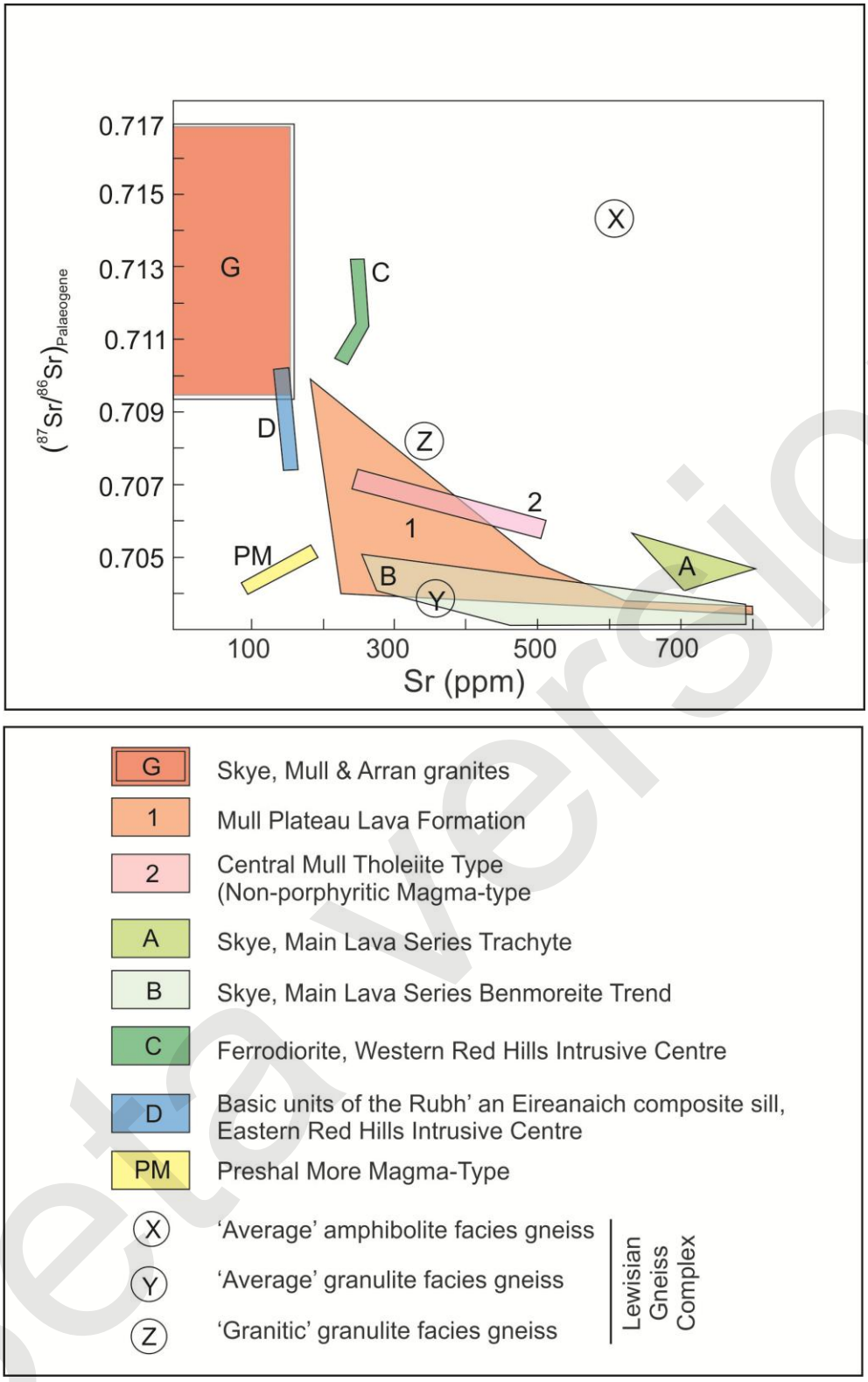


Figure 10-3: $(^{87}Sr/^{86}Sr)_{Paleocene}$ against total Sr for basaltic rocks, granites and crustal materials in the HIP. Depicted fields are: G, Skye, Mull and Arran granites; 1, Mull Plateau Lava formation; 2, Central Mull Tholeiite Magma-type (or Non-Porphyritic Magma-type); A, SMLS Trachyte; B, SMLS Benmoreite Trend; C, Ferrodiorite unit of the Marsco Hybrids, Western Red Hills Intrusive Centre, Skye; D, Basic units of the Rubh' an Eirèannaich composite sill, Eastern Red Hills Intrusive Centre, Skye; PM Preshal More Magma-type; X, 'Average' amphibolite-facies Lewisian gneiss; Y, 'Average' granulite-facies Lewisian gneiss; Z, 'Granitic' granulite-facies Lewisian gneiss. See main text for discussion and references.

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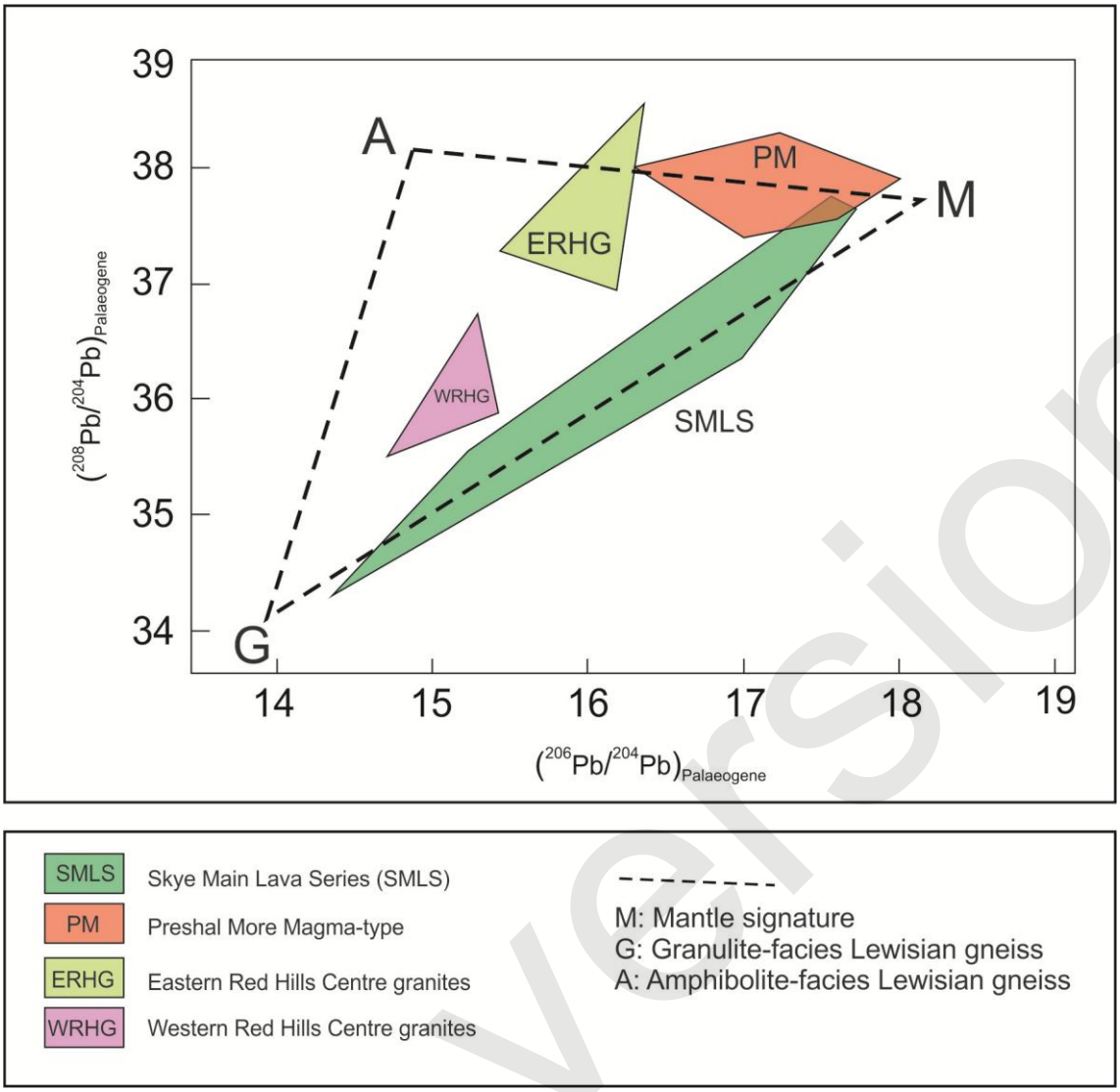
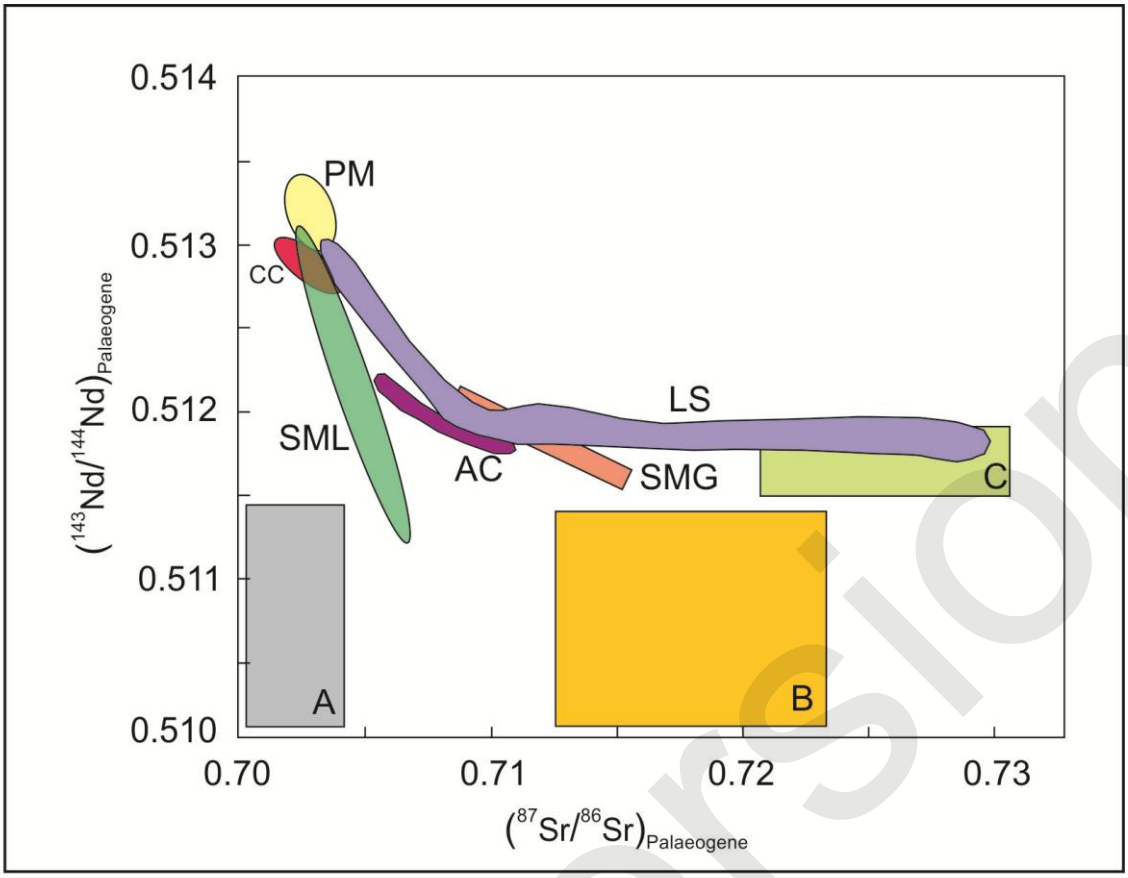


Figure 10-4: Plot of Pb isotope data for Skye lavas and granites compared to compositions of crustal and Mantle mixing components involved in their formation (after Dickin et al. 1987). M, Estimated 'average' composition of Mantle-derived magmas for Skye at 60 Ma; G, 'Average' granulite-facies Lewisian gneiss; A, 'Average' amphibolite-facies Lewisian gneiss.

The Sr-isotope signatures of the SMLS indicate different histories for the Benmoreite and Trachyte trends (Moorbath & Thompson 1980; Figure 10-3). Within the former, fractional crystallization in granulite-facies lower crust has left the Mantle signature unmodified, whereas in the latter contamination by (radiogenic) amphibolite-facies upper crust has occurred. Taking Nd-isotope data and trace-element concentrations into account, it is evident that the SMLS magmas underwent fractional crystallization near to the base of the crust (Thirlwall & Jones 1983; Dickin *et al.* 1987). By combining Sr- and Nd-isotope data it is possible to identify contamination trends and the fields occupied by particular contaminants (Figure 10-5).

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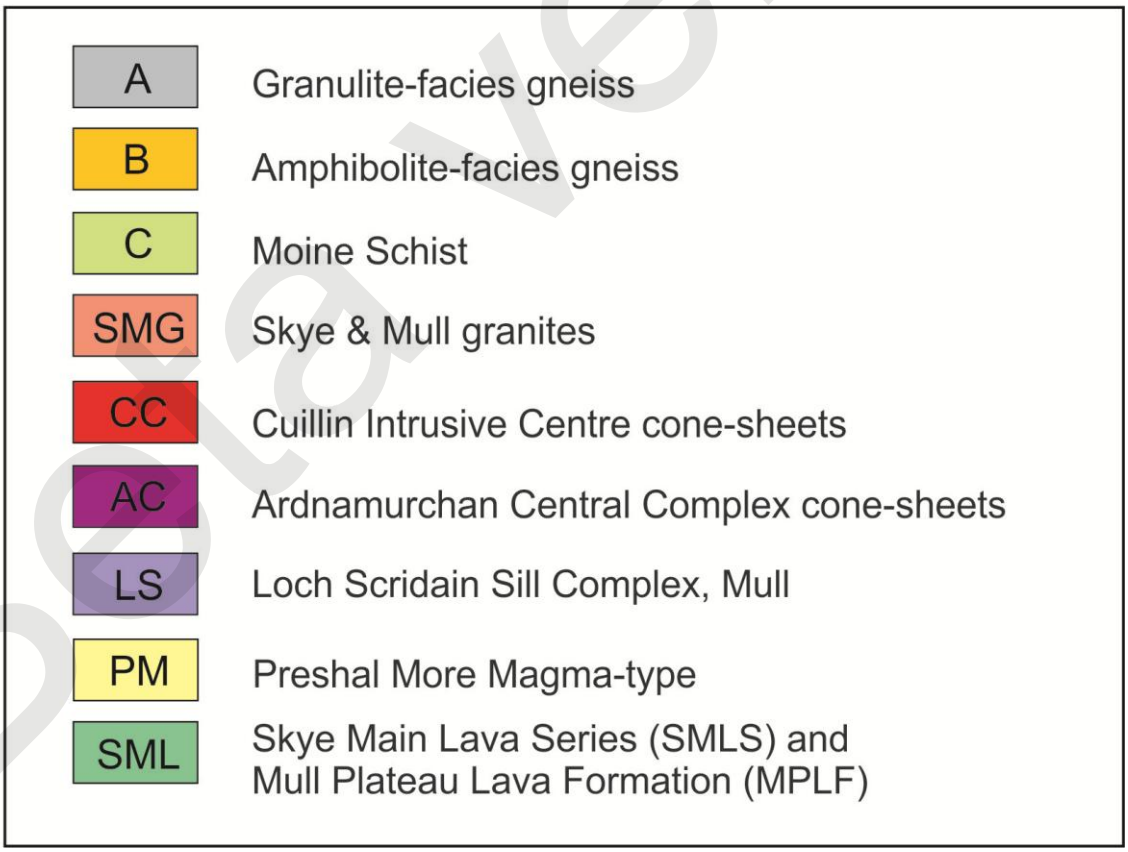


Figure 10-5: Combined $(^{143}Nd/^{144}Nd)_{Palaeogene}$ vs. $(^{87}Sr/^{86}Sr)_{Paleocene}$ whole-rock data for various magma-types and crustal materials of the Hebridean Igneous Province.

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Similarly, Pb-isotope data can be used to identify lower and upper crustal contaminants and the available data suggest that in most instances almost complete equilibration between magma and crust took place, possibly by some sort of vapour transfer mechanism and involving the dominant intermediate composition crustal rocks (Dickin 1981) (Figure 10-4).

Magmas of the SMLS and the MPLF that show significant amounts of contamination, based upon their relatively high values of $(^{87}Sr/^{86}Sr)_{Paleocene}$, have relatively higher concentrations of Ba, Rb, Sr, Th and the light rare-earth-elements (LREE), introduced during the incorporation of crustal melts produced by wall-rock melting (Thompson *et al.* 1982). The most contaminated lavas have the most primitive compositions because they had the highest temperatures (Kerr *et al.* 1999). Contamination of the Preshal More basalt (or magma-type) differs for that of the SMLS and the MPLF and was of the AFC (assimilation during fractional crystallization) type, involving upper crustal amphibolite facies Lewisian gneiss or Moine Supergroup psammites and pelites. A similar contamination story has been deduced for the various intrusive units of the Cuillin Intrusive Centre (Dickin *et al.* 1984; Bell *et al.* 1994). The tholeiitic basalt Staffa Magma-type lavas close to the base of the sequence in SW Mull have different trace-element characteristics from the Preshal More lava. Contrasting opinions exist as to the origins of these isotopically contaminated lavas. One model involves picritic melts that underwent fractional crystallization at the Moho, followed by contamination involving partial melting of fusible quartzo-feldspathic lithologies in granulite-facies gneisses, then AFC type contamination involving Moine Supergroup psammites and pelites in the upper crust (Thompson *et al.* 1986). Kerr (1999) offered a different model, involving SMLS/MPLF type magma, that underwent crustal contamination. Peate *et al.* (2012) demonstrated from the analysis of melt inclusions within olivine crystals in primitive (Mg-rich) lavas from the lower part of the Mull Plateau Group that crust assimilation, or contamination, took place both during and after olivine crystallization.

Contamination is also linked to whether magma temporarily stops during ascent, whereby some of the most primitive lavas having stalled in the lower crust and are amongst the most contaminated. Font *et al.* (2008) demonstrated from a detailed Sr and Pb isotope analysis of rims and cores of plagioclase crystals within lavas of the Skye Lava Field that individual crystals have greater differences than that recorded by hundreds of whole-rock samples. The isotopic differences within the plagioclase crystals are attributed to variable degrees of magma contamination during fractional crystallisation and ascent. Most of the lava sequence predominantly involved only contamination by lower crust, whereas the MORB-like tholeiitic basalt magma, erupted to form the youngest preserved lavas, the Talisker Formation, additionally were contaminated by upper crustal material.

Furthermore, the variability of the isotopic signatures between different plagioclase crystals within a single lava suggests their aggregation from different storage and differentiation sites during ascent. Composite intrusions occur at Drumadoon and An Cumhann on the west coast of Arran. The Drumadoon Sill comprises a central quartz-feldspar porphyritic rhyolite unit flanked by xenocrystic basaltic andesite units, and intervening zones of quartz-feldspar porphyritic dacite. Contamination by continental crust occurred during ascent; mixing during emplacement produced the dacite (Kanaris-Sotiriou & Gibb 1989; Meade *et al.* 2009). The presence of xenocrysts within the basaltic andesite units indicates a mixing event prior to emplacement. The isotopic signatures of the Drumadoon rocks indicate that, despite being located within the Midland Valley Terrane, they interacted during their ascent with Grampian Terrane crust (Meade *et al.* 2009).

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10.4 Primary compositions of Mantle-derived magmas and depths of generation

Experimental studies of and trace-element data from the SMLS indicate an origin by partial melting of a garnet lherzolite Mantle at a depth of *ca*. 60 km (Thompson 1974; Thompson *et al*. 1980). The Preshal More basalt (magma-type) was subsequently generated by a greater degree of melting of the residuum. The remaining unmelted Mantle was of harzburgitic composition. A similar model may be applied to the Mull lavas (Thompson 1982). For the Mull lavas, Kerr *et al*. (1999) suggested a model involving three groups (or magma-series), each achieving their composition by differing depths of melting, with time. First, deep melting of garnet lherzolite produced the MPLF magmas, giving way to shallower melting of garnet-poor lherzolite to yield the so-called Coire Gorm and Central Mull Tholeiite magma-types (the latter a re-named Nonporphyritic Central Magma-Type). Involved in this model are variable amounts of fractional crystallization and contamination by a range of crustal materials.

Scarrow & Cox (1995) re-examined the geochemistry of the Skye lavas and advocated a model involving decompressive melting of abnormally hot Mantle to yield picritic magmas, which then evolved by fractionation of olivine and chrome-spinel. Final melt segregation (i.e. equilibration) from the Mantle took place within the depth range *ca*. 60–110 km at temperatures in the range 1390– 1510°C. The melts that separated at the greatest depth were nepheline-normative, whereas the shallower melts were hypersthene-normative. This model is in broad agreement with that advocated by Thompson *et al*. (1972) and Thompson (1974).

In order to explain the overall relatively low concentrations of incompatible trace-elements within the Paleocene lavas of NW Scotland, Morrison *et al*. (1980) and Thompson (1982) suggested that prior extraction of highly alkaline (lamprophyric) melts during the Permian resulted in a depleted Mantle that then yielded up the various magmas in the Paleocene. Lateral Mantle heterogeneity may also have been at least partially responsible for the depleted geochemical characteristics, although this is very difficult to model, given that crustal contamination processes were also involved in producing the final geochemical signatures of the lavas (Morrison *et al*. 1980).

10.5 Ultrabasic and basic magmas of the central complexes

Evidence for parental magma compositions to ultrabasic and basic units of the central complexes might be deduced from uncontaminated chilled margin material, where fractionation events are least likely to have occurred. Alternatively, spatially and genetically associated suites of minor intrusions may provide insights into magma compositions. Among the latter, the swarms of cone-sheets associated with the Cuillin Intrusive Centre of the Skye Central Complex (Bell *et al*. 1994), the Ardnamurchan Central Complex (Geldmacher *et al*. 1998) and the Mull Central Complex (Kerr *et al*. 1999), are of the MORB-like Preshal More Magma-type (akin to the Central Mull Tholeiite Magma- Type; cf. Kerr *et al*. 1999). Fractionation of these centrally-emplaced magmas appears to have taken place at relatively shallow depths (*ca*. 10 km, 3 kbar). Chilled margins to gabbroic intrusions are of similar composition, for example, the Ben Buie Gabbro, Mull (Skelhorn *et al*. 1979).

The parental magmas to the various intrusions of ultrabasic rock were of a somewhat more primitive composition. The most convincing evidence for genuinely picritic magmas, with MgO *ca*. 18 wt%, comes

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from thin dykes on Rum, interpreted to have a 'transitional' compositional affinity, generated by partial (6-7%) melting of a depleted Mantle at a depth of *ca*. 100 km, i.e. straddling the spinelgarnet transition. Initially crystallized olivines were extremely magnesian, at Fo_{93}. The layered peridotites of the Eastern Layered Intrusion on Rum had a parental picritic magma with 15–20 wt% MgO (Greenwood *et al*. 1990; Volker & Upton 1990), whereas the troctolitic and gabbroic units formed from a basaltic melt with *ca*. 10 wt% MgO. Alkaline affinities are, however, suggested for at least some of the Rum magmas, based on late-stage analcime-bearing segregation veins (Kitchen 1985).

10.6 Minor intrusions

Dykes, cone-sheets, sills and plugs all provide geochemical data concerning magma-types and magmatic processes involved in their formation. In particular, they provide unique evidence of high-level, *in situ* processes that are inferred to have been involved in the geochemical evolution of the lavas, but for which no obvious 'visual' evidence is retained. For example, they reveal the presence of crustal xenoliths and the significance of contamination processes; and, the accumulation of crystal-rich zones in dykes and sills and flow differentiation.

10.7 Dyke swarms

Within the Skye Dyke swarm, *ca*.70% of the intrusions are of the Preshal More Magma-type and are most abundant within the axis of the swarm and close to the Cuillin Intrusive Centre (Mattey *et al*. 1977). Such dykes appear to be genetically related to the swarm of cone-sheets that are dominant within the NW and SE quadrants of the Cuillin Intrusive Centre. Walker (1993b) concluded that the dykes were emplaced, down-rift, during periods of relatively rapid crustal extension, whereas the cone-sheets were emplaced during periods of slower extension. Xenolithic, plagioclase-megacrystic gabbro-anorthosite dykes in north Skye also appear to have been formed from the Preshal More Magma-type and preserve abundant evidence of flow differentiation and the incorporation of cognate xenoliths (Donaldson 1977). The remaining dykes are dominated by compositions belonging to the SMLS Magma-type, although dykes with a 'hybrid' composition are also noted, the so-called Fairy Bridge Magma-type, with a major-element signature akin to the SMLS Magma-type but with trace-element characteristics more akin to the Preshal More Magma-type (Mattey *et al*. 1977). Dykes with SMLS affinities and with evolved compositions, for example, trachytes, tend to occur only in the vicinity of remnants of the lava fields that contain abundant evolved lavas and are, in general, close to the central complexes.

The Mull Plateau Lava Formation and Central Mull Tholeiite magma-types are both represented within the Mull Dyke swarm (Kerr *et al*. 1999). The distal members of the swarm in NE England, for example, the Cleveland Dyke, belong to the latter (Macdonald *et al*. 1988) and have Sr-isotope signatures indicating significant crustal contamination, predominantly by Moine metasedimentary material (Moorbath & Thompson 1980).

Intrusions belonging to the Mull Dyke Swarm in southern Scotland, distant from the Mull Central Complex, range in composition between basalt and dacite (Macdonald *et al*. 2010). Two groups are recognised: a group where the compositional variation is the result of fractional crystallisation, and a group that is the product of variable degrees of mixing of basaltic and silicic magmas. In a detailed geochemical study of basalt/dolerite dykes from the Mull Dyke Swarm and the Islay-Jura Dyke swarm, Hole *et al*. (2015) identified compositions where there was minimal interaction with, and contamination by, crustal materials: Mg# 60-75; εNd_{58} *ca*. 8; $^{206}Pb/^{204}Pb$ *ca*. 17.5; and $^{87}Sr/^{86}Sr < 0.704$. Geochemical modelling of these uncontaminated magmas indicates that compositions with convex upwards REE patterns required

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< 10% melting of the Mantle in the garnet-spinel transition zone, whereas compositions with LREE-depleted or flat REE patterns required up to 20% melting of a (shallower) spinel lherzolite Mantle. Hole *et al.* (2015) estimated that the HIP melting event, peripheral to the proto-Icelandic plume (see below, with a Mantle potential temperature of up to 1560°C, i.e. the temperature the Mantle would have at the Earth's surface if it ascended without losing heat), had a lower maximum Mantle potential temperature of *ca.* 1530°C.

Ishizuka *et al.* (2017) recognised different contamination mechanisms for dykes proximal and distal to the Mull Central Complex. Dykes < 30 km from the central complex predominantly involved vertical flow of magma, contrasting with lateral flow for the more distal dykes. The proximal dykes achieved their geochemical signature first by their storage in and assimilation of basement gneiss of the Lewisian Gneiss Complex, followed by similar processes in shallower Moine Supergroup psammites. Distal dykes, of intermediate (andesitic) composition, are the product of large volumes of basic and silicic magmas mixing as the source chambers below the Mull Volcano emptied, possibly being responsible for one or both of the caldera-forming events (see above).

The Eocene sapphire-bearing xenolithic monchiquite dyke of Loch Roag, Harris, has high concentrations of Ba and the light rare-earth elements (Menzies *et al.* 1989; Failthfull *et al.* 2012), unlike all other dykes within the HIP. However, an isotopic age of *ca.* 47 Ma implies a Paleocene affinity, even though the chemistry of the dyke is more akin to Permo-Carboniferous lamprophyres, common throughout NW Scotland (Upton *et al.* 1998).

10.8 The Cnoc Rhaonastil Boss, south Islay

This relatively small doleritic boss or stock contains dominant alkali olivine-dolerite and analcime-dolerite facies of SMLS/MPLF association/magma-type. However, rare segregations or pods of coarse-grained nepheline syenite attest to extremely efficient closed-system fractionation, most likely involving some form of filter pressing mechanism (Hole & Morrison 1992). Such evolved compositions are rare, only approached elsewhere by facies within the Shiant Isles Sill of the Little Minch Sill-Complex (see below). Minerals with high concentrations of trace-elements within the syenites are documented by Preston *et al.* (1998, 2000a, 2000b).

10.9 Sill-complexes

The two significant onshore sill-complexes outlined above are of contrasting compositional affinities: (i) the Little Minch Sill-complex, of SMLS/MPLF Magma-type (alkali olivine basalt); and, (ii) the Loch Scridain Sill-complex, of Preshal More Magma-type (tholeiitic basalt). The Little Minch Sill-complex comprises leaves that range in composition between picrite, through analcime-olivine-dolerite to rare syenite (Gibb & Henderson 1996; Gibson 1990). The alkaline affinities of the sills are similar to the SMLS/MPLF magmas. However, Sr- and Nd-isotope data indicate that AFC processes have taken place, involving contamination of the magma(s) by up to 20% of amphibolite-facies Lewisian gneiss (Gibson 1990). A phase-equilibria study of the magmas involved in the Little Minch Sill Complex, co-genetic crystal-rich and crystal-poor variants, indicates that the associated magma chamber was located at a depth of *ca.* 25 km and fed magmas to depths as shallow as 3 km from the contemporaneous land surface (Nicoli & Matthews 2019).

The xenolithic Loch Scridain Sill-complex comprises three distinct groups: Group 1, tholeiitic basalts and andesites, mainly aphyric and with Preshal More Magma-type affinities; Group 2, plagioclase and pyroxene-porphyritic andesites and dacites; and, Group 3, rhyolites (Preston *et al.* 1997, 1999). The

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geochemical trend from Group 1 through 2 to 3, is one of increasing concentration of incompatible trace elements and elevated values of radiogenic Sr and Pb, interpreted as an AFC process involving a high-Nd partial melt of Moine metasedimentary material, but not wholesale assimilation of pelite. The Group 3 rhyolites represent partial melts of Moine Supergroup pelite, whereas the Group 2 andesites and dacites formed by bulk mixing of Group 1 basalt magma and Group 3 rhyolite magma. The xenoliths within the Loch Scridain sills are of two types: cognate, mainly of gabbroic and peridotitic material representing cumulate assemblages (Preston & Bell 1997) and accidental crustal types (Preston *et al.* 1999). Within the latter category, certain of the xenoliths have behaved in a relatively refractory manner, for example, Moine quartzites. The unusual mullite- and cordierite-bearing aluminous buchites, however, are the result of melting of crustal materials. A two-stage process is recognised by Preston *et al.* (1999), involving a first stage that yields a rhyolitic melt, now represented by the Group 3 rhyolite sills, and a second stage bulk melting of the residual, more aluminous pelites. Reaction between these aluminous melts and the hot basaltic sill magmas resulted in abundant crystallization of plagioclase around the rims of the aluminous buchites, producing anorthosite mantles (Preston *et al.* 1999; Dempster *et al.* 1999). Essentially, within these xenolithic sills we are seeing evidence of a contamination process 'frozen in', which more typically is deduced from elevated radiogenic isotope signatures in, for example, xenolith-free lavas.

10.10 Silicic rocks

Rocks of silicic composition occur predominantly within the central complexes, as ring-intrusions, bosses and stocks, and range in composition between monzogranite and peralkaline granite. More rarely, dykes, sills, lavas and pyroclastic deposits cover a similar compositional range. The most controversial aspect of these silicic rocks is their origin: are they the products of extreme fractional crystallization of basic magma and, if so, which type of magma?; or, are they the consequence of partial melting of crust by the voluminous and hot basic and ultrabasic magmas as they migrated through the crust? Most likely, both mechanisms will have occurred in tandem and, in examining the geochemistry of the silicic rocks, attempts should be made to distinguish examples where one or other process has been dominant.

Early ideas on the genesis of the granites were dominated by fractional crystallization (e.g. Harker 1904, 1908; Bailey *et al.* 1924; Richey *et al.* 1946). Following on, the pendulum swung towards favouring partial melting processes (e.g. Wager 1956; Wager *et al.* 1953, 1965; Brown 1963; Dunham 1968; Thompson 1969). With the development of rapid geochemical analysis, including isotope spectrometry, significant progress was made in trying to recognize how the two contrasting processes could be distinguished through the compositions of the magmas/rocks produced. Early isotope studies included Moorbath & Bell (1965) and Moorbath & Welke (1969), who considered the whole-rock Sr- and Pb-isotopes of various volcanic and intrusive rocks from Skye, respectively. The Sr data suggest a partial melting model, whereas the Pb data infer a mixed model, involving Mantle and crustal lead. Subsequent studies have confirmed that Mantle and crustal isotopic components are present in all of the igneous units of the HIP: although Mantle- and crust-dominated examples are recognized (Walsh *et al.* 1979; Moorbath & Thompson 1980; Dickin 1981; Dickin *et al.* 1984). The crustal component comes from the same sources recognised for the lavas: lower and upper crustal gneisses (granulite- and amphibolite-facies, respectively) of the Lewisian Gneiss Complex, Moine Supergroup metasedimentary rocks (pelites and psammites), Dalradian pelites, and Torridonian feldspathic sandstones and siltstones. Interpretation is somewhat hampered by the alteration processes associated with the development of meteoric water (hydrothermal) circulation systems during and after emplacement, and which had the potential to cause modifications to rock chemistry (Taylor & Forester 1971; Forester & Taylor 1977; Ferry 1985a, b; Ferry *et al.* 1987). Careful sampling appears to have minimized this potentially serious problem.

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Three compositional groups were recognised by Thompson (1982) for Paleocene granitic rocks throughout the HIP, on the basis of mineralogy (hence major-elements), trace-elements and isotope geochemistry. Thompson (1981) concluded that granites within the primitive and peralkaline categories are the product of simple crystal-liquid fractionation, involving quartz, plagioclase, alkali feldspar, Fe–Ti oxides and apatite. From a study of the whole-rock REE signatures of Skye granites, Thorpe *et al.* (1977) and Thorpe (1978) identified the similarity between the REE profiles of lavas of the SMLS/MPLF Magma-type and the granites and suggested a link through fractional crystallization (Figure 10-6). Thompson (1982) demonstrated, however, that a similar match could be made by mixing *ca.* 80% of uncontaminated Preshal More basalt magma with *ca.* 10% each of granulite- and amphibolite-facies gneiss to yield a contaminated liquid which, after fractional crystallization, would give granitic liquids. It is therefore possible that both basaltic magma-types could produce granitic liquids. However, with the potential of so many compositional parameters, it is possible to produce almost any 'desired' result.

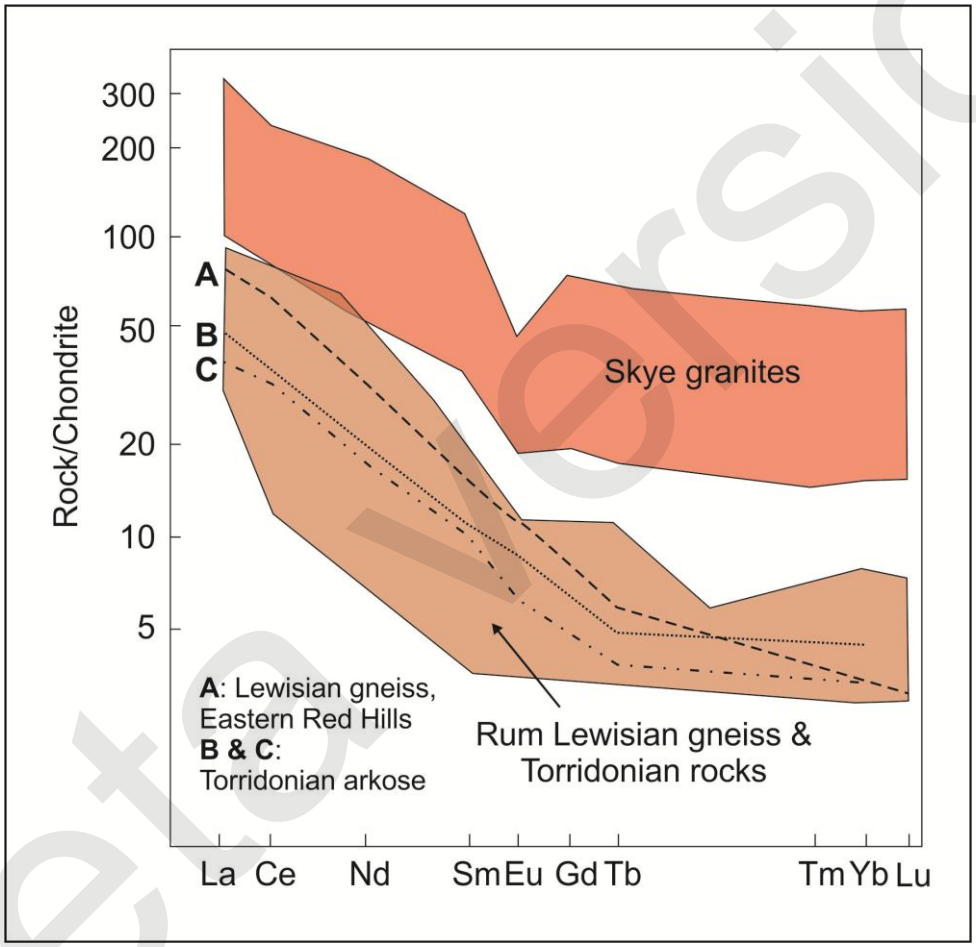


Figure 10-6: Chondrite-normalised rare-earth-element (REE) abundance data for Skye granites compared to Lewisian and Torridonian crustal formations from Skye and Rum (after Thorpe *et al.* 1977). Depicted compositional field and symbols are: Skye granites; Rum Lewisian and Torridonian rocks; and, A, Lewisian gneiss (Eastern Red Hills Intrusive Centre, Skye); and, B & C, Typical Torridonian arkoses from close to the Skye Central Complex.

Peraluminous granites can be produced by melting granodioritic to tonalitic Lewisian gneiss or Torridonian feldspathic sandstone and siltstone at low pressures (1 kbar H_2O pressure) at temperatures above 715°C (Thompson 1981). Such lithologies bulk melt at temperatures above 930°C, similar to the liquidus temperatures of Hebridean granites (Thompson 1983). If a bulk melting model is appropriate, then there would be the expectation that a typical granodioritic or tonalitic gneiss would have the same

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trace-element signature as a peraluminous granite. This is not the case and, therefore, such a model cannot be correct.

Dickin (1981) concluded from his analysis of radiogenic isotope data for Skye granites that the dominant (but not the only) crustal component is amphibolite-facies gneiss, i.e. the same contaminant identified for the Preshal More magma (see above). Contamination appears to have been selective, with the initial breakdown of certain accessory minerals within granulite-facies gneiss, but without significant partial melting of the gneiss. Subsequently, the contaminated Preshal More magma underwent AFC within amphibolite-facies gneiss in the upper crust. Here, partial melting did occur, and these melts mixed with the silicic liquids generated by the fractionation of the contaminated Preshal More basaltic magma. Thus, a hybrid origin for Skye granites was advocated. An example of a granitic intrusion containing at least a proportion of partial melt of Torridonian sedimentary rock is the Coire Uaigneich Granite of the Cuillin Intrusive Centre on Skye (Wager *et al.* 1953; Brown 1963). Dickin & Exley (1981) demonstrated a hybrid origin for this granite, involving the combination of a partial melt of feldspathic sandstone and siltstone and liquids produced by fractional crystallization of Cuillin-type (i.e. Preshal More) basic magma. The presence of zircons of Torridonian type (detrital) within the granite emphasises the link with partial melting processes (Exley 1980).

The origin of the granites within the Mull Central Complex was discussed by Kerr *et al.* (1999). Two groups of granites were recognized by Walsh *et al.* (1979): 'early granites' belonging to Centre 1, and 'late granites' belonging to centres 2 and 3. Kerr *et al.* (1999) concluded that the two types can be distinguished on a variety of geochemical plots. All the granites have hybrid origins, involving fractional crystallization combined with crustal input. The amount of crust appears to be greatest in the oldest granites, and the youngest granites have the most-evolved compositions.

The granites of the North Arran Granite Pluton are the product of fractional crystallisation of basaltic liquids but also contain a crustal contribution from the basement (here Neoproterozoic to early Palaeozoic Dalradian meta-sedimentary rocks) (Dickin *et al.* 1981; Meighan *et al.* 1992). To the south, the peralkaline Ailsa Craig Granite contains virtually no crustal component (Harrison *et al.* 1987).

10.11 Magma mixing and mingling processes

Magma mixing and mingling were important magmatic processes throughout the HIP, particularly within the intrusive environment. Classic examples of intrusions involving contrasting basic and silicic magmas include the composite dykes and sills associated with the Skye, Mull, Ardnamurchan and Arran central complexes, and hybrid ring-dykes such as Marsco, Loch Bà and Glen More. Mixing appears to have taken place prior to and during emplacement: within the basic units, xenocrystic quartz and alkali feldspar are preserved, whereas in the silicic units, clots of basic material are common. The basic magmas tend to be somewhat evolved, within the compositional range ferrobasalt through to ferroandesite, with low Ti/P values (Bell 1983; Marshall & Sparks 1984; Sparks 1988; Bell & Pankhurst 1993).

Within the composite sill at Rubh' an Eirèannaich in the Eastern Red Hills district on Skye, there are completely gradational contacts between the marginal basic units and the central silicic unit (Harker 1904). Trace-element and Sr-isotope data indicate that the basic magma had a composition consistent with *ca.* 50% fractional crystallization of a tholeiitic basalt magma contaminated with crust (Bell & Pankhurst 1993). Mixing at the interface between the contrasting magmas lead to a compositionally gradational zone over *ca.* 30 cm.

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Within the ring-dykes of the central complexes, more-thorough mixing occurred, although each intrusion displays certain unique characteristics. Analysis of the compositions of the rocks, however, points to similar liquids being involved. The Loch Bà Ring-dyke of Centre 3, Mull, consists of a dominant felsite-rhyolite-welded tuff, with up to 10 vol% of dark glassy inclusions ranging in composition from ferrobasalt through to rhyolite, with tholeiitic ferroandesite particularly common (Sparks 1988). Within the dominant silicic material are phenocrysts of quartz, sanidine and other minerals, all of which are present as xenocrysts within the inclusions. Similarly, within the Marsco Hybrids of the Western Red Hills Intrusive Centre, Skye, the basic unit, ferrodiorite, contains xenocrysts of quartz and is therefore of hybrid character. Within the silicic unit, a porphyritic felsite, the quartz occurs as phenocrysts. Simple bulk mixing calculations suggest that the hybrid rock found in close association with the basic and silicic units, referred to as marscoite by Harker (1904), was produced by the mixing of two parts intermediate (i.e. ferroandesite) magma with one part silicic (porphyritic felsite) magma (Wager *et al.* 1965; Bell 1983). Farther north, on Glamaig, another part of the ringdyke contains the less homogeneous hybrid, 'glamaigite', comprising small basic inclusions within a pale more-silicic matrix. Such heterogeneous materials would be, even at moderate temperatures, homogenized by diffusion in less than two years, or less than one year at magmatic temperatures (Thompson 1980). Thus, the preservation of such textures implies very rapid quenching after mixing.

Within the Western Red Hills Intrusive Centre, the Glamaig Granite carries abundant small xenoliths of basaltic material and clots of mafic minerals. Thompson (1980) interpreted these as evidence for the mixing of basaltic magma into a dominant granitic magma body. The basaltic material has the characteristic evolved Ti/P signature typical of tholeiitic andesite. To explain the genesis of these hybrid intrusions, and others throughout the HIP such as the Glen More Ring-dyke on Mull and the classic 'net-veined' complexes in Centre 2, Ardnamurchan, and in the St Kilda Central Complex, it is necessary to infer compositionally zoned magma bodies or chambers at depth (Thompson 1980; Bell 1983; Marshall & Sparks 1984; Sparks 1988; Preston 2001). The roof zone of such chambers will be dominated by a cap of low-density rhyolitic magma. Below will be a strongly zoned more basic body of magma, zoned downwards from rhyolitic through dacitic to ferrobasaltic.

The compositional range of the glassy inclusions within the Loch Bà Ring-dyke is particularly compelling evidence for the zoned nature of such an underlying basic magma body (Sparks 1988). Mixing along the interface between the rhyolite magma cap and the underlying zoned body of magma will cause the initial stage of hybridization recognized by the presence of xenocrysts in the essentially unmixed basic and silicic units preserved within the intrusions. Troll *et al.* (2021) concluded from the isotopic signature of the mixed-magma Loch Bà Ring-dyke on Mull that a considerable contribution to the rhyolitic component was from the partial melting of Moine Supergroup psammites and pelites, whereas the mafic component of the ring-dyke has a Mantle-like signature, devoid of crustal contamination. Spatially and temporally associated granites also have a crustal component, but less than that of the ring-dyke. Emplacement of these ring-dykes and the final disposition of the remnant parental basic and silicic magmas and the newly formed hybrid materials caused by their mixing, will depend upon the dynamic processes that occur within the ring fractures as the central blocks subsided and the magmas mingle/mix and are forced upwards. Sustained high temperatures will lead to thorough mixing and homogenization. Superheating of the rhyolitic magma by the hotter basic magma may lead to vesiculation in the former and the formation of a gas-charged pyroclastic fluid, as suggested for the Loch Bà Ring-dyke (Sparks 1988). Surface eruptions of mixed-magma material may occur but are not preserved within the now deeply dissected lava fields of the province.

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10.12 The nature of the plume(s) associated with North Atlantic volcanism in the Paleocene

The magmatism that commenced in the early Paleocene with the impact of the proto-Iceland Plume in the North Atlantic region continues today in Iceland, which is located on the axis of a now substantially smaller plume (Saunders *et al.* 1997) (Figure 1).

The source of the plume is assumed to have been a thermal boundary layer deep (but at unknown depth) within the Mantle (White & McKenzie 1989, 1995). There are some obvious problems with the simple plume model proposed by White & McKenzie (1989): high-temperature picritic magmas were involved with the magmatism around the margins of the North Atlantic Igneous Superprovince (NAIS), for example, on Mull and Rum (Kerr 1995; Emeleus 1997), and MORB-type basalts are recognized within the marginal areas, for example, Skye (Thompson 1982) and appear to have been derived from a depleted Mantle. To produce picritic melts would require a Mantle temperature above 1450°C, at least 150°C above the normal, or ambient, temperature.

To explain the very rapid commencement of the magmatism associated with the plume (White & McKenzie 1989, 1995; Saunders *et al.* 1997), together with the spatial, temporal and volumetric relationships of the various magmas throughout the NAIS, it can be concluded that the plume had the following characteristics: (i) high initial temperatures; (ii) melting that may be attributed to the decompression of upwelling Mantle during lithospheric rupture and plate separation; and, (iii) magma ascent that appears to have been controlled by pre-existing lithosphere 'topography' or 'thin-spots' (Thompson & Gibson 1991), or magma ascent along a planar surface rather than a point source (Saunders *et al.* 1997).

The widespread magmatism that occurred during the initial impact phase of the plume collapsed into a linear rift system during and after plate separation and the commencement of sea-floor spreading at *ca.* 55 Ma. However, continued sporadic activity away from the rift zone at this time suggests a degree of lateral migration away from the site or sites of upwelling. In order to identify hot, plume-related magmas that were generated at depth from melts derived from the relatively cooler Mantle through which the plume ascended, geochemical discriminants have been sought. Fitton *et al.* (1997) concluded that normal mid-ocean ridge basalts (N-MORB) can be distinguished from 'plume' magmas derived from a deeper and less-depleted Mantle source by their Nb–Y–Zr signatures and that, on a log (Nb/Y)-log (Zr/Y) plot, it is possible to distinguish between magmas derived from these contrasting sources. The degree of melting, crustal

contamination processes and any subsequent hydrothermal alteration do not appear to upset the Nb-Y-Zr signature, and therefore offer a simple discriminant as to whether a particular batch of magma (now represented by extrusive or intrusive units) may be attributed to a deep-sourced plume or was simply the product of partial melting in the upper, depleted mantle.

Within the Iceland Neovolcanic Zone, plume magmas with depleted and enriched signatures have been erupted. N-MORB basalts (i.e. derived from the depleted upper mantle and not related to Mantle plume magmatism) occupy a field below the 'plume array'. Thus, to identify plume-related magmas within the HIP, their location on this plot should reveal their affinities. The wealth of geochemical (major, trace, REE and isotope) data now available for the basaltic rocks of the HIP (lavas, dykes, and cone-sheets) provides considerable insight as to the nature and dynamics of the proto-Iceland Plume and its source region. Scarrow *et al.* (2000) concluded that early Paleocene magmatism was dominated by the polybaric melting

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of an anhydrous Fe-rich plume source Mantle. Kent & Fitton (2000) suggested that the geochemical data are consistent with

the derivation of the basaltic magmas not from a single Mantle source but two sources: (1) Icelandic (plume) Mantle; and, (2) hot N-MORB-like Mantle forming an outer envelope to the plume. With time, the proportion of 'Icelandic' material involved in the melting regime below the Hebrides, more than 1000 km from the axis of the plume, increased and then decreased, relative to N-MORB type. Chambers & Fitton (2000) have demonstrated a change in the geochemical signature of the lavas on Mull, essentially coincident with the incoming of the Coire Gorm Magma-type (Kerr 1995), at the base of the Ben More Pale Member. The underlying Ben More Main Member has an N-MORB signature, derived from the relatively cool outer part of the plume, whereas the younger volcanic rocks have been sampled from the hotter, 'core' of proto-Iceland Plume material. Helium isotope data for certain Skye lavas are consistent with an origin from the proto-Iceland Plume (Stuart *et al.* 2000).

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11 Paleocene and later structure

11.1 Introduction

The Paleocene and later structures of the Inner Hebrides, the adjoining Scottish Mainland, and Arran were strongly influenced by structures inherited from Mesozoic and earlier times (Figure 11-1) (Chapter 4). These earlier structures include major, NE-trending faults and lineaments dating from the Caledonian Orogeny or earlier, and large, predominantly N-S-orientated Mesozoic sedimentary basins with their bounding faults. There is evidence that at least some of these structures were reactivated during the Paleocene magmatism and it has been postulated that they were major factors in determining the sites of the Paleocene central complexes (e.g. Richey 1961) and the thick lava successions (Walker 1979). Parts of the lava fields are extensively faulted, and localised faults and folds occur within and around the central complexes.

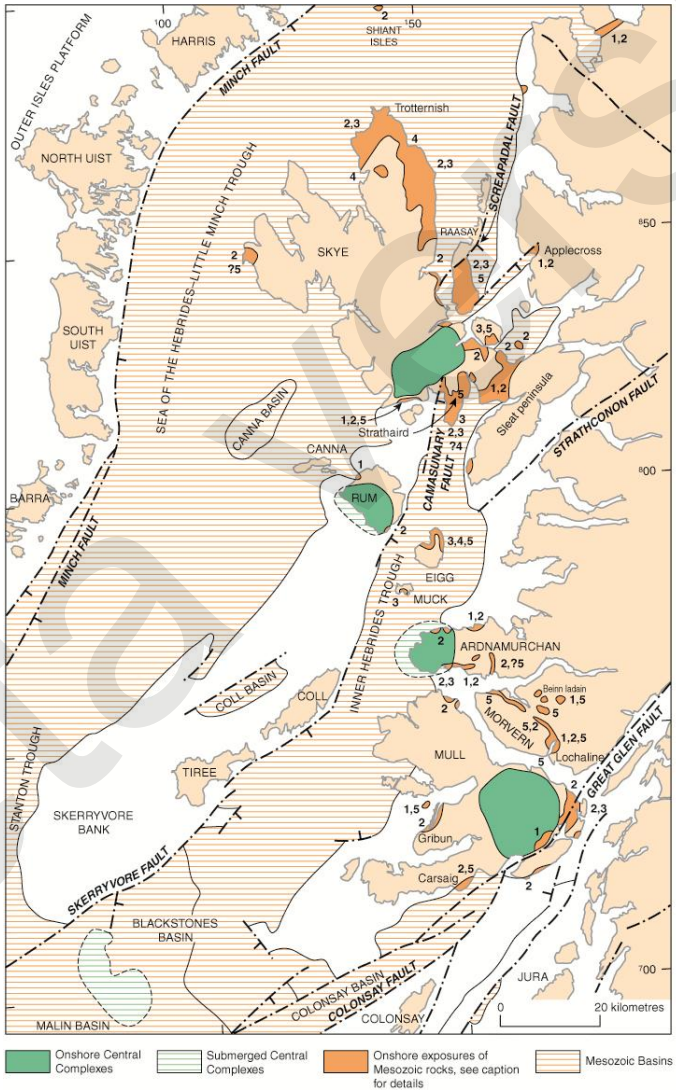


Figure 11-1: Simplified geological map of the Inner Hebrides showing the location of Mesozoic basins, the location where Mesozoic rocks occur onshore, and the locations of the Paleocene central complexes. Pre-Mesozoic rocks are uncoloured (after Fyfe *et al.* 1993). 1, Permo-Triassic; 2, Lower Jurassic; 3, Middle Jurassic, 4, Upper Jurassic; 5, Upper Cretaceous.

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11.2 Major faults

The central complexes of Skye and Rum are situated on, or close to, the N-S-trending Camasunary—Skerryvore Fault (Figure 11-1), which defines the western edge of the Inner Hebrides Basin. At Camasunary, on Skye, the fault affects Torridonian and Mesozoic strata but there is little, if any, displacement of the overlying Paleocene lavas, which belong to the Skye Lava Field/Group. Beyond the Blà Bheinn area, the northern continuation of the fault is uncertain, but it has been suggested that the Loch Screapadal Fault on Raasay represents its northern continuation. This is a major, post-Mid Jurassic fault that is offset by a zone of NW-trending sinistral strike-slip faults between Raasay and the Red Hills (Butler & Hutton 1994). South of Skye, there is evidence of Paleocene, or post- Paleocene, movement on the continuation of the Camasunary Fault, since gently SW-dipping lavas of the Eigg Lava Formation crop out on Eigg but not on the east coast of Rum (except as faulted slivers in the central complex; Chapter 9). Still farther south, both Coll and Tiree are formed of the Lewisian Gneiss Complex, although down-faulted Paleocene lavas occur beneath the sea a short distance to the east of both islands.

The Great Glen Fault cuts across SE Mull, where it has disturbed Mesozoic and earlier rocks but not the Paleocene lavas (Figure 11-1) (Chapter 4). There is, however, evidence of displacements on this fault system that post-date dykes near Mull (Holgate 1969). Basaltic dykes, of presumed Paleocene age, intrude the Caledonian Strontian Granite and Moine rocks on the west side of Loch Linnhe. The probable SE continuation of this swarm on Lismore appears to have been offset dextrally by the intervening Great Glen Fault, with further dextral offset by the NE-trending Lynn of Lorn Fault, situated between Lismore and the Scottish Mainland to the SE. There has been a total of almost 30 km of post-Paleocene dextral displacement of the dyke swarm, 20 km of which was on the Lynn of Lorn Fault. From an analysis of the Neogene drainage pattern on both sides of the Great Glen, Holgate (1969) suggested that the final dextral movement was considerably later than the emplacement of the Mull Central Complex. Consequently, the SE continuation of the Mull Regional Dyke Swarm also should be offset dextrally and be represented by dykes well to the south and SW of Oban. However, there is no indication of any offset of the pronounced linear magnetic anomalies associated with the Mull swarm to the SE of Mull, which head directly towards the Mull Central Complex. Furthermore, the dense dyke swarm at Oban and to the SE includes significant numbers of felsic dykes and a few composite dykes, which are indicators of proximity to an associated central complex. Thus, the available evidence indicates that, although the southern extension of the Skye Regional Dyke Swarm may have been displaced, little movement has occurred on the Great Glen Fault since the emplacement of the Mull Central Complex and the Mull Regional Dyke Swarm.

11.3 Structure of the lava fields

11.3.1 Skye

The lava field of northern Skye is dissected by numerous faults and has been gently folded. The lavas have been broken into many blocks by major, continuous faults trending between NW and N-S, and shorter faults trending approximately NE. The fault pattern is well displayed in west-central Skye where the lava stratigraphy is known in reasonable detail (Williamson & Bell 1994). The broad structure of the lava field is interpreted as an early, shallow NW-trending syncline, the core of which is occupied by the more evolved lavas. This earlier folding is attributed to loading that resulted from lava accumulation. Later folds developed along a N-S to NE trend and were related to Oligocene and younger events; one such syncline is responsible for the preservation of Oligocene strata in the offshore Canna Basin (England 1994).

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11.3.2 Eigg and Canna

The lavas of both the Eigg and the Canna lava formations are either flat-lying or dip at low angles. Normal faults are common. On Eigg there is evidence that a NNW-trending fault that affected the Mesozoic strata was reactivated after accumulation of the Eigg Lava Formation (Emeleus 1997).

11.3.3 Mull

The detailed stratigraphy of the latest part of Mull Lava Field has not been determined and therefore only the broad outline of the structure is known. The lavas of NW Mull, Ulva, Ardmeanach and the eastern part of the Ross of Mull, and the thick Ben More succession are generally flat-lying or dip gently, although evolved lavas SE of Ben More are involved in folds associated with the emplacement of the central complex (see below). Away from the central complex, the base of the lavas crops out in the south at Carsaig Bay, in the west at Gribun, and in the north at intervals on the coast between Tobermory and Bloody Bay. This may indicate that the lavas form a broad NNW-trending syncline in NW Mull. Several NNW- to NW-trending faults occur on the island of Ulva, towards the western end of Ardmeanach and south of Loch Scridain. On the Ross of Mull, near Ardtun, the lava outcrop terminates at the WNW-trending Loch Assapol Fault, where they are thrown down against Moine Supergroup metasedimentary rocks.

11.3.4 Morvern

The lavas on Morvern are cut by NNW- to N-trending faults and are faulted out in the east at the N-trending Inninmore Fault, where they are thrown down against Moine Supergroup psammitic gneisses. The base of the volcanic sequence drops from an altitude of *ca.* 400 m on Beinn Iadain in the east to sea level near Auliston Point in the west, a distance of *ca.* 13 km. Much of the change in altitude is the result of faulting but some is due to post-depositional tilting of the lavas. Near to the Inninmore Fault, the lavas directly overlie Cretaceous, Jurassic, Triassic and Moine rocks, indicating a measure of uplift and erosion before the lavas were erupted. Elsewhere in Morvern, the lavas generally overlie the thin Paleocene Gribun (Beinn Iadain) Mudstone Formation, which in turn usually overlies on the equally thin Upper Cretaceous Clach Alasdair Conglomerate Member (compare with Hancock 2000; Mortimore *et al.* 2001). There is thus only slight evidence for erosion between the Late Cretaceous and the Paleocene in this district.

11.4 Structures associated with the central complexes

Country-rocks adjacent to the central complexes are commonly folded and faulted because of the emplacement of the intrusive units. These features are most apparent around intrusive centres where granites or other silicic intrusions are present (Chapter 9).

11.4.1 Skye

The lavas and earlier rocks around the Cuillin Intrusive Centre on Skye are generally flat lying and appear little disturbed, except for gentle folds in Glen Drynoch. However, there is considerable disruption of country-rocks adjoining both the Western and Eastern Red Hills intrusive centres. Paleocene lavas, Mesozoic sedimentary rocks and Torridonian sandstones on the northern slopes of Glamaig and on Scalpay appear to define part of a dome over the Western Red Hills granites. In the Eastern Red Hills there is a suggestion of doming of Mesozoic and earlier sedimentary rocks over the Beinn na Caillich Granite.

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The Beinn an Dubhaich Granite occupies the core of the Broadford Anticline, an anticlinal structure in Lower Palaeozoic Durness Group dolostones. However, the granite cuts across, and hence postdates, the folds (Holroyd 1994). Folding of lavas and Mesozoic rocks in the Coire Uaigneich area, west of Loch Slapin, is attributed to granite emplacement (Butler & Hutton 1994).

11.4.2 Rum

The gentle regional dip of Torridonian Supergroup sandstones towards the WNW to NW is greatly disturbed on the northern margin of the Rum Central Complex. Where they are in faulted contact with the Western Granite and the Northern Marginal Zone (Chapter 9), the beds dip outwards at over 50° towards the NW in the west, changing progressively to a NE direction in the east. There is little folding or tilting of the strata next to the Eastern Layered Intrusion, although large masses of Torridonian sandstone at Mullach Ard, at Welshman's Rock and in parts of southern Rum appear to have slid away from the area of the central complex, with minor folds in places. These structures formed during the early stages in the growth of the central complex, when central uplift led to doming, and major peripheral faults initiated the Main Ring Fault (Chapter 9). The central complex is cut by the N-S-trending Long Loch Fault. There is evidence of movement on this fault both before and after the emplacement of the central complex, and that it acted as a feeder zone during emplacement of the layered intrusions.

11.4.3 Ardnamurchan

On the eastern margin of the Ardnamurchan Central Complex, the NNW-trending Loch Mudle Fault throws down Paleocene lavas and Mesozoic rocks to the east. Apart from this and some other minor faults, there is little sign of disturbance of the lavas and earlier rocks. At the western end of the peninsula, however, the Mesozoic sedimentary rocks generally dip away from Centre 2 and the northern edge of Centre 3, suggesting a dome-like structure. In contrast to the doming on Skye and Rum, this appears to be associated with predominantly gabbroic intrusions; however, there must have been a substantial contribution to uplift by the intrusion of the multitude of cone-sheets (e.g. LeBas 1971).

11.4.4 Mull

One of the most notable structural features of the Hebridean Igneous Province is the set of concentric folds that almost encircle the Glen More and Beinn Chaisgidle intrusive centres on Mull (Bailey *et al.* 1924). These folds are developed in the surrounding older lava sequence and the various subjacent pre-Paleocene rocks. They include the Loch Spelve and Loch Don anticlines and the Duart Bay and Coire Mòr synclines. South of Loch Don, Dalradian Supergroup meta-limestones and phyllites form the core of a N-trending anticline, flanked successively by late-Silurian andesitic lavas, Lower and Middle Jurassic sandstones and mudstones, and Paleocene lavas. These major structures continue to the north and NW, where Jurassic rocks form the core of the Craignure Anticline as far as Craignure Bay, with Moine Supergroup rocks exposed in the core between Craignure Bay and Scallastle Bay. Elsewhere, the folds generally involve Paleocene basaltic lavas and, on the eastern flanks of Ben More, mugearite lavas near to the top of the lava succession. It is suggested that the folds formed in response to the early intrusive events in the central complex, but their age is not well understood. Furthermore, the area enclosed by the folds is domed and the folds may owe their origin to gravity-driven movement as the dome developed. From evidence in the Loch Don area, it has been suggested that doming and folding were initiated prior to eruption of the Paleocene lavas (Cheeney 1962; Walker 1975a), but Bailey (1962) considered the evidence to be inconclusive. Near Sgùrr Dearg, the folds are cross-cut by, and thus predate, volcaniclastic breccias of the central complex.

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11.4.5 Arran

There is significant deformation of the country-rocks surrounding the Paleocene North Arran Granite Pluton. Throughout the SW Highlands, the Dalradian Supergroup rocks strike consistently NE-SW, but on Arran they strike approximately parallel to the near-circular outline of the Outer Granite (of the North Arran Granite Pluton) over *ca*. 270° of arc. The structure is well illustrated by the outcrops of distinctive black, slaty and phyllitic meta-mudstones on the west and NW margin of the pluton. To the north of the granite, between Loch Ranza and Catacol, the Dalradian rocks form a concentric fold, termed the Catacol Synform. Offshore, between Catacol and Imichar Point, Permo-Triassic sandstones occur in the core of a concentric synclinal structure affecting Dalradian and Carboniferous rocks. On the eastern side of the granite, the country-rocks responded to granite emplacement by a combination of folding and faulting, with reactivation of pre-existing faults in the structurally complex area near Corrie. Locally, near Pirnmill on the west coast, there are small reverse faults inclined towards the granite, some of which cut Paleocene dykes. South and SE of the granite, doming has affected sedimentary rocks of Devonian, Carboniferous and Permian age, for example in Glen Cloy, west of Brodick. This deformation is attributed to the diapiric rise of the Outer Granite (England 1992b). The later Central Arran Ring-complex cuts across the domed country-rocks of the pluton and there is some evidence that the country-rocks adjacent to the ring-complex are also domed on its south and SE side, although indifferent exposure makes verification difficult.

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12 Late Paleocene and Neogene

An absolute age, or date, for the cessation of magmatic activity in the Hebridean Igneous Province (HIP) is yet to be agreed. A radiometric age as young as 55.7 Ma has been determined for a late-stage vitrophyre ('pitchstone') dyke that cuts the Beinn na Caillich Granite, in the Eastern Red Hills Intrusive Centre on Skye and an age of 55.89 ± 0.15 Ma for the nearby Beinn an Dubhaich Granite appears to confirm the interpreted late-stage chronology of these intrusive units.

Application of low temperature thermochronology techniques provides some constraints on the cooling history of the igneous units (Dobson *et al.* 1990), whereby their cooling history, together with the timing of any uplift and erosion events, can be estimated. Specifically, (U-Th)/He data from zircon crystals and apatite fission-track data from many of the intrusive units, which constrain when these rocks cooled to a temperature below *ca.* 110 °C, yield near-identical ages to the crystallisation ages. Consequently, we may deduce that the Paleocene intrusions cooled very rapidly, most likely involving contemporaneous uplift and erosion, although any estimate as to how close to the Earth's surface these rocks were when they locked in their low-temperature cooling age will depend upon, amongst other factors, the geothermal gradient at the time.

Indirect corroborative evidence for the rapid erosion of the volcanic edifices of the province is outlined in Chapter 6, whereby the Minginish Conglomerate Formation within the Skye lava sequence contains exotic and distinctive clasts of various extrusive and intrusive lithologies derived by the unroofing of the Rum Volcano to the south (Williamson & Bell 1994). At a later stage in the development of the lava field, a significant erosional topography developed, with steep-sided river valleys that were subsequently infilled by fluvial conglomerate and a lava erupted from the relatively late-stage Cuillin Volcano, now represented by the unroofed Cuillin Intrusive Centre (Bell & Williamson 2013).

However, apatite fission track data for certain small-volume intrusions, for example the various units of the Marscoite Suite of the Western Red Hills Intrusive Centre, give a mid-Eocene cooling age, *ca.* 45-47 Ma (Dobson *et al.* 1990), suggesting continued high, but sub-magmatic, temperatures, or a discrete pulse of heat at this time. This age is similar to a relatively well-determined $^{40}Ar/^{39}Ar$ plateau (crystallisation) age of *ca.* 45 Ma for the late-stage xenolithic Loch Roag dyke (Chapter 7) (Faithfull *et al.* 2012), a monchquite (an alkali-rich basic igneous rock with phenocrysts of clinopyroxene and biotite), interpreted to be the product of small degrees of mantle melting, which intrudes the basement Lewisian Gneiss Complex on the Isle of Lewis, to the NW, and which is on-trend with other intrusions of the Skye Regional Dyke Swarm. Thereafter, the constructional geological record of the HIP goes quiet as ocean floor spreading gets underway in the NE Atlantic Ocean and the continental lithospheric plate that includes Greenland drifts north-westwards.

Following on from the Paleocene magmatic events, a protracted period of intense weathering and erosion occurs, starting in early Eocene times (*ca.* 56 Ma), coincident with the short-lived Paleocene-Eocene Thermal Maximum (PETM) (Kennet & Stott 1991), when the global average temperature was more than 8 °C warmer than today, through the Eocene (*ca.* 56-34 Ma) and Oligocene (*ca.* 34-23 Ma) epochs, into the Neogene Period (which consists of the Miocene (*ca.* 23-5.3 Ma) and Pliocene (*ca.* 5.3-2.6 Ma) epochs (Figure 12-1).

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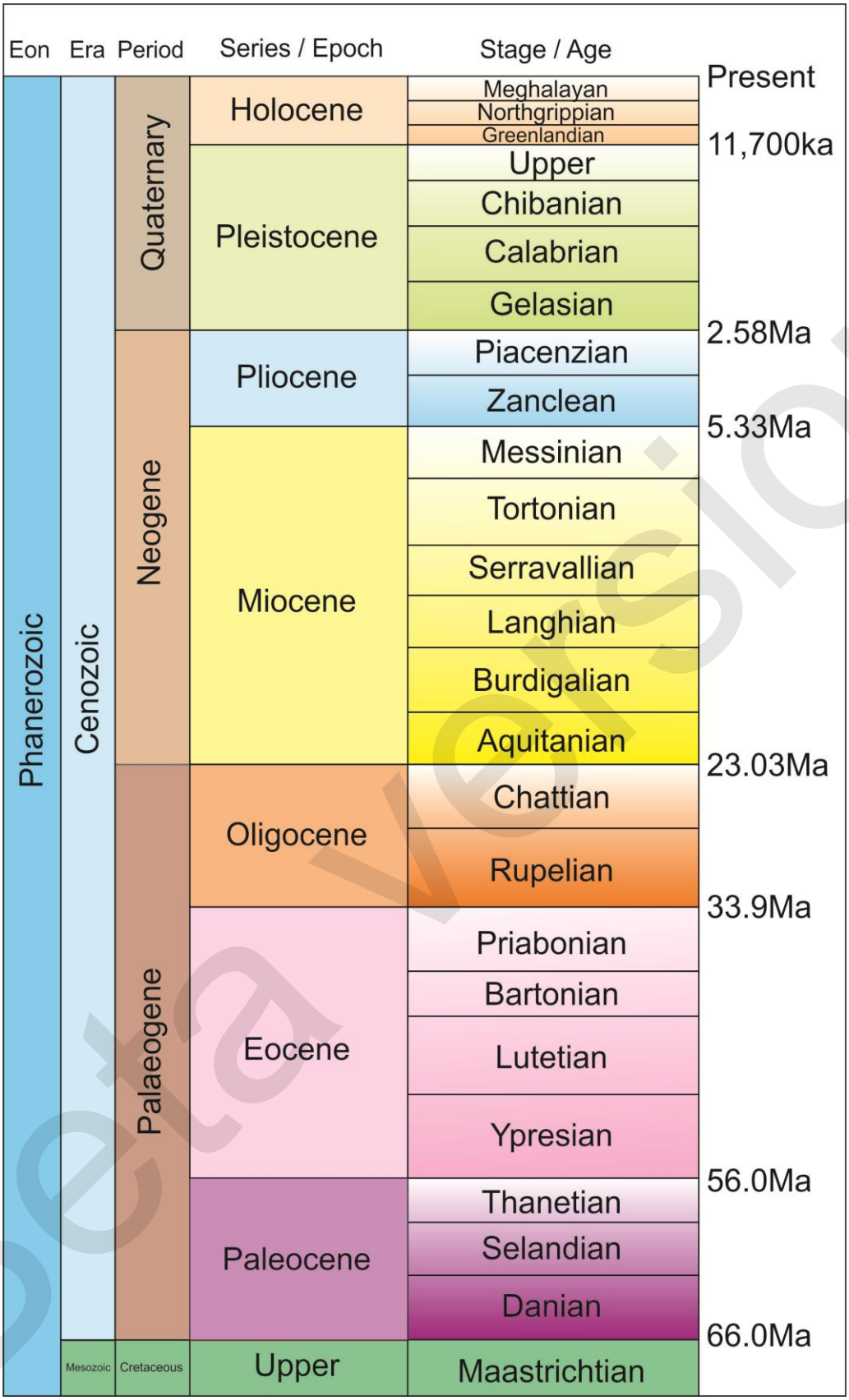


Figure 12-1: Cenozoic chronostratigraphy.

The age of the weathering is uncertain, but much of it may date from the Eocene to the Miocene, when chemical alteration would have been favoured by the prevailing warm, wet conditions. Preserved examples of Eocene to Pliocene weathering profiles include: deeply-inweathered dolerite dykes, basic

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and ultrabasic rocks on Rum, where they are found both beneath glacial deposits and in pockets up to 21 m deep on bare rock surfaces (e.g. Ball 1964); the ferrodiorite unit of the Marscoite Suite of the Western Red Hills Intrusive Centre, Skye (Figure 12-2); and, deeply-weathered gabbro in Coire na Banachdich in the Cuillin, Skye. It is possible that the large landslipped masses at The Storr and The Quiraing in north Skye started to develop during this period.

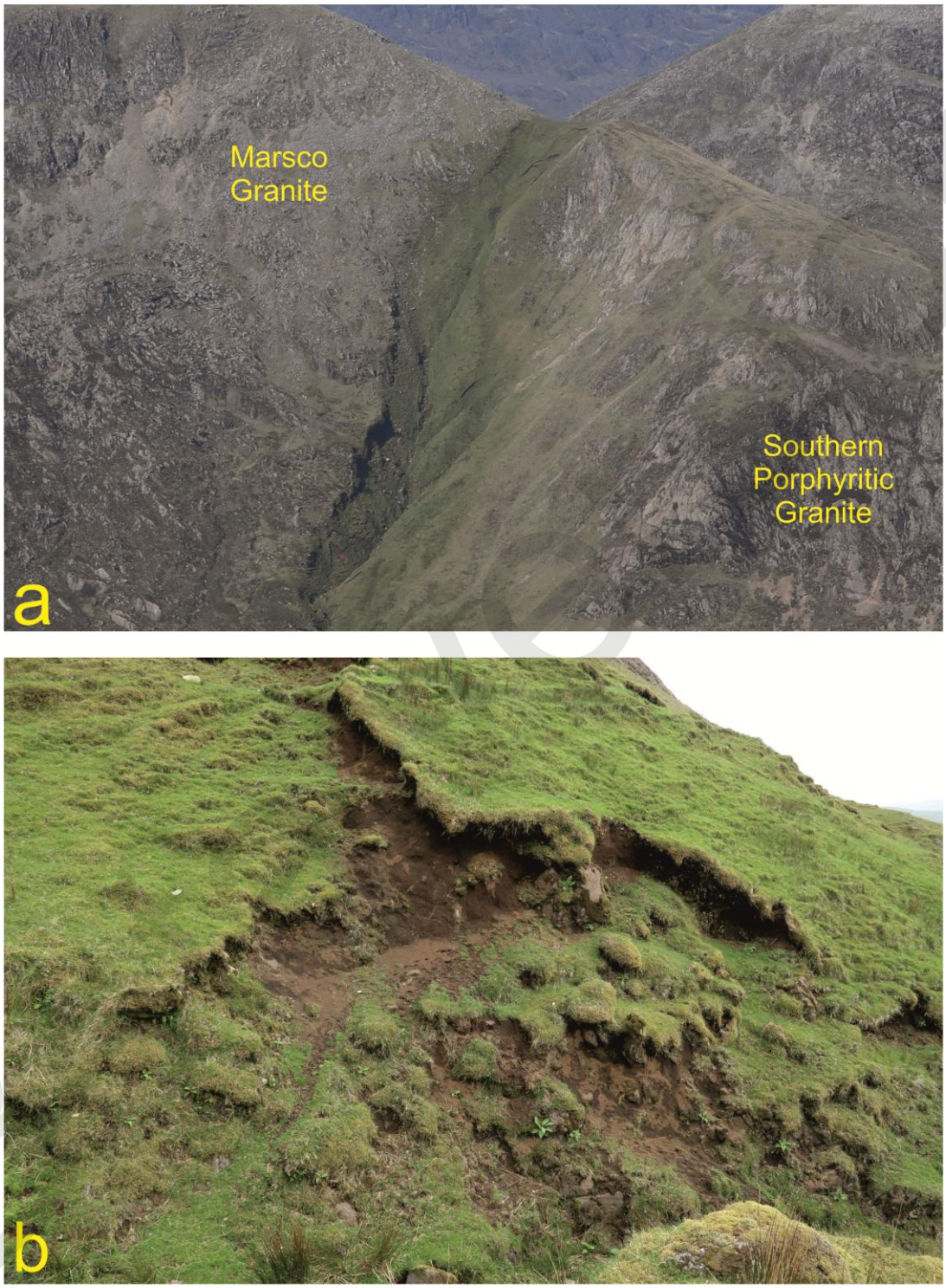


Figure 12-2: (a) Outcrop of the Marscoite Suite of the Western Red Hills Intrusive Centre, forming a prominent verdant gully on the east side of Druim Eadar Dà Choire; and, (b) detail of the deeply weathered ferrodiorite unit of the Marscoite Suite within the gully.

Other examples of similarly deep weathering profiles, best demonstrated in dolerite intrusions, are recognised in Trotternish on Skye (Figure 12-3; Figure 12-4), and on the Ardnamurchan peninsula (Figure 12-5).



Figure 12-3: Deeply weathered dolerite sill with spheroidal (onion-skin, or doleritic) weathering, Rubha nam Brathairean, Trotternish, Skye.



Figure 12-4: Deeply weathered dolerite sill with spheroidal (onion-skin, or doleritic) weathering, Peingown, NW Trotternish, Skye. Pole *ca.* 1 m long.



Figure 12-5: Deeply weathered dolerite plug with spheroidal (onion-skin, or doleritic) weathering, Bourblaige, SE Ben Hiant, Ardnamurchan.

Much of the North Arran Granite Pluton (Chapter 9) has a distinctive 'block joint' development, which in turn influences how it weathers (Figure 12-6).

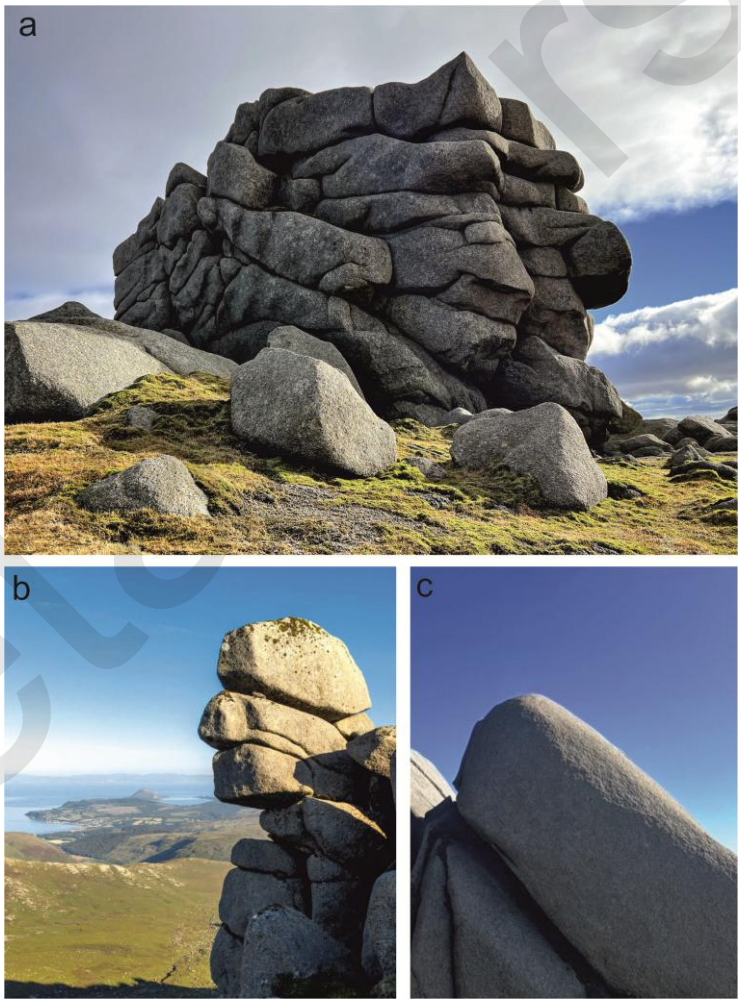


Figure 12-6: Distinctive 'block joint' development in the Paleocene North Arran Granite Pluton, forming: (b) 'The Old Man of Tarsuinn': and (c) The Rosetta Stone (on the summit of Cir Mhòr).

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Rapid erosion of the Highlands of the Scottish Mainland provided detritus which accumulated in the North Sea Basin in considerable thicknesses during Paleocene to early Eocene times. The major sediment influxes may have been pulsed, in response to the Paleocene igneous activity and were not equalled later (e.g. Zeigler 1981; White & Lovell 1997). In contrast, the late Eocene to Neogene was a period of relatively limited uplift and erosion of the Highlands and western Scotland (Hall 1991). Terrestrial sedimentary rocks of Oligocene age occur in restricted basins and have been proved in a borehole in the Little Minch, SE of Harris and in the Canna Basin SW of Skye where they are *ca*. 1000 m thick (Fyfe *et al*. 1993). Oligocene rocks also occur on the Blackstones Bank where they partly conceal the central complex. The sediments consist of carbonaceous mudstones with plant debris and lignite deposited in a floodplain or lacustrine environment of swamps and fens.

Extensive weathering did occur during the Pleistocene and continues to the present day, with physical rather than chemical processes causing disaggregation.

The present-day landscape has clearly developed over a considerable period of time, but the history of uplift and erosion is poorly understood. The distribution of the Cretaceous rocks (Chapter 3) and the sedimentary lithologies associated with the Eigg Lava Formation (Chapter 6) indicate that when igneous activity began at *ca*. 61 Ma, relief over the area was generally subdued. It has been recognised that there was rapid, deep subaerial erosion during the Paleocene (e.g. Hall 1991). This erosion occurred as the central complexes grew, and the lava fields developed; there is evidence that the Rum Central Complex was unroofed in less than 1.6 Ma (Hamilton *et al*. 1998; Chambers *et al*. 2005). Evidence from the central complexes indicates that mountain massifs formed by a combination of igneous intrusion and extrusion, faulting and folding. Major differential movements occurred in and around all of the central complexes, and evidence for this is particularly well preserved on Mull and Arran.

The Cuillin (*ca*. 970 m OD), certain of the Red Hills and the Kyleakin Hills of Skye (*ca*. 720 m OD) all show a similar altitude of their main summits and this is also apparent elsewhere. In the past, this similarity in the levels has been attributed to marine planation during a relative rise in sea level, most likely in the Neogene. This interpretation is almost certainly wrong because most uplift occurred during the Paleocene and sea level dropped during the Neogene. Tilted planation surfaces of subaerial origin have been recognised, for example on Skye outwith the Cuillin (at 500 to 700 m, 400 to 450 m. and 250 to 300 m OD) and a lower surface is identified at 80 to 120 m OD at many places in western Scotland, including Skye, Rum, Ardnamurchan and Mull (Le Coeur 1988). These planation surfaces are now attributed to uplift that occurred in several stages, and it can be inferred that some tectonic tilting and deformation took place subsequent to the Paleocene igneous activity. Evidence for faulting of the lower planation surface during the Neogene is found in the offshore extension of the surface east of Lewis, which is thrown down to the east by about 150 m on the Minch Fault. Flexing of the surface occurs at a few places; for example, it is tilted towards the west on either side of the Sound of Raasay (Le Coeur 1988).

Cooling intensified at around 2.6 Ma and culminated with the onset of the so-called Ice Age (Ballantyne & Lowe 2016), which marks the beginning of the present period, the Quaternary, comprising the Pleistocene (2.6 Ma – 11,700 yr BP) and Holocene (11,700 yr BP to today) epochs. These glacial and associated inter-glacial processes and events are considered in detail in Chapter 13.

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13 Quaternary



The Quiraing Landslip, Trotternish, North Skye

13.1 Introduction

Since the onset of the Quaternary Period at approximately 2.6 Ma BP, the Highlands and Islands of western Scotland have experienced repeated episodes of glaciation during the Pleistocene Epoch (Figure 13-1) (Ballantyne & Gordon 2014). During the Early Pleistocene, glaciation was probably restricted to high ground, with ice confined largely to mountain summits and upland plateaux. In the Hebrides, such early glaciation is inferred indirectly, as direct terrestrial evidence has largely been removed by later ice-sheet erosion. However, locally preserved weathered bedrock and blockfield remnants on high ground in areas such as the Cuillin of Skye and the Rum Cuillin have been interpreted as indicating limited erosion by early, cold-based ice or ice-free conditions (Ballantyne 2010; Hall & Ballantyne 2006).

Following the Mid-Pleistocene Transition at *ca*. 0.75 Ma, glacial–interglacial cyclicity shifted towards longer, higher-amplitude cycles, and the middle latitudes of Europe repeatedly supported extensive ice sheets (Clark *et al*. 2006). During these phases, the British–Irish Ice Sheet (BIIS) expanded across much of the Scottish Mainland and extended westwards into the Inner Hebrides. On Skye, Mull and Arran, this transition is recorded by widespread ice-moulded bedrock, glacial striae, and the dispersal of erratics demonstrating interaction between locally sourced ice and Scottish Mainland-derived ice (Sissons 1980; Ballantyne 2017). Major marine troughs, including the Sea of the Hebrides and the Inner Sound, functioned as fast-flowing ice-stream corridors that exerted strong control on ice dynamics (Bradwell *et al*. 2008; Scourse *et al*. 2009).

Glaciation during the Middle and Late Pleistocene was characterised by broadly rhythmic expansion and decay of ice sheets driven by orbital forcing. Prolonged cold intervals (glacials) were separated by shorter interglacials with climates broadly comparable to the present day. At least five major glacial-interglacial cycles with an average periodicity of *ca*. 100 ka are recognised during this interval (Lisiecki & Raymo 2005). Within individual glacials, shorter-term climatic oscillations occurred, with colder stadials and relatively milder interstadials. In the Inner Hebrides, evidence for such oscillations includes complex suites of moraines on Skye and Mull, and spatially variable relative sea level histories recorded by raised shorelines and marine limits (Dawson 1988; Ballantyne & Dawson 2003).

The most recent and geomorphologically dominant glaciation occurred during the Dimlington Stadial of the Late Devensian (*ca*. 26-19 ka BP), when the BIIS reached its maximum extent (Figure 13-2) (Clark *et al*. 2012). During this phase, much of Skye, Mull and Arran was overridden by ice. However, central mountain massifs, notably the Cuillin and Red Hills of Skye, functioned as independent ice caps that generated radial ice flow and deflected Scottish Mainland-derived ice into adjacent troughs (Sissons 1967; Ballantyne 2017). The absence of Scottish Mainland erratics from these upland areas, contrasted with their widespread presence on Raasay, Scalpay and Soay, defines the spatial limits of local ice dominance (Peacock 1984; Ballantyne & Small 2018).

Extensive erosion during the Dimlington Stadial removed much of the sedimentary and geomorphological evidence of earlier glaciations, as well as pre-Quaternary weathering mantles (Chapter 12). Consequently, the terrestrial Quaternary record of the Hebrides is highly fragmentary prior to *ca*. 26 ka BP, with earlier glacial events inferred largely from offshore stratigraphy and indirect geomorphological indicators (Stoker *et al*. 2009). Many Late Pleistocene ages, particularly between *ca*. 26 and 60 ka BP, are expressed in radiocarbon years and require calibration, as uncalibrated radiocarbon ages increasingly underestimate true calendar ages with increasing antiquity (Reimer *et al*. 2020).

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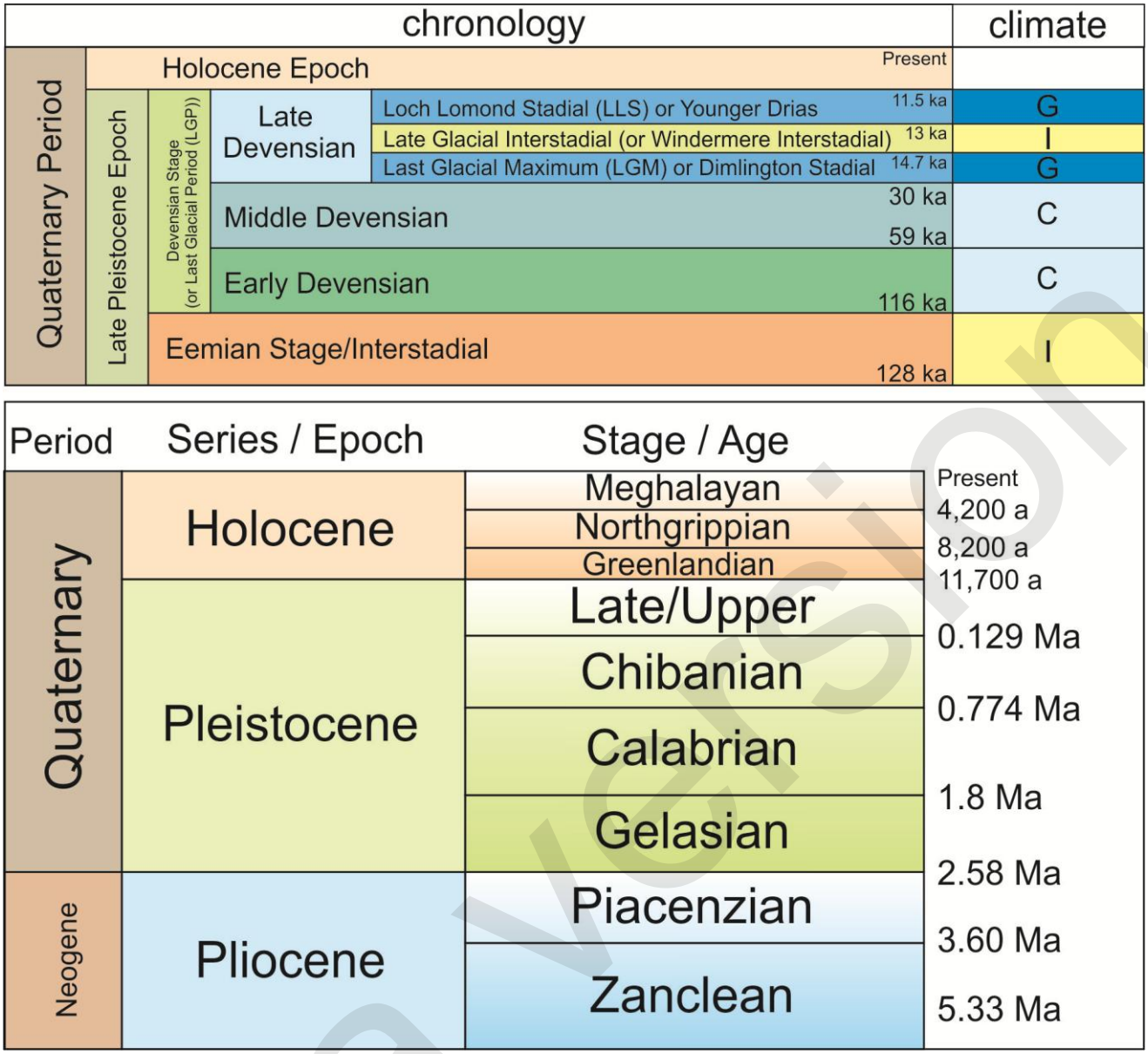


Figure 13-1: Subdivisions of the Quaternary Period. Climate conditions: G, glacial; I, interglacial; C, cold conditions, with possible glacial and interglacial periods. ka = thousand years.

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Epoch	Age		Stadials/ interstadials	Glaciations and *raised shorelines*	Boundary age BP
Holocene	Flandrian (interglacial)			*Late-Postglacial shorelines, 3000 BP* *Main Postglacial Shoreline, 7000 BP* *Buried beaches, 9000 BP*	10 000* (11 500)
Pleistocene	Devensian (glacial)	Late Devensian	Loch Lomond Stadial	Loch Lomond (re)advance	11 000* (13 000)
			Windermere (Late-glacial) Interstadial	*Main Late-glacial shoreline*	
				Early Late-glacial shorelines	13 000* (14 700)
			Dimlington Stadial	Main Late Devensian Glaciation	26 000* (30 000)
		Mid Devensian	Upton Warren Interstadial		59 000
		Early Devensian	Brimpton Interstadial	High rock platforms†	
				(Early Devensian glaciation?)	
			Chelford Interstadial		116 000
	Ipswichian (interglacial)				128 000

† or during the Dimlington Stadial (Sissons, 1982)

* These ages are in radiocarbon (C^{14}) years before present day (BP). Due to difficulties in calibration, they are significantly younger than ages based on other methods, such as counting seasonal layers in ice or sediment. In the Late Devensian and Flandrian, radiocarbon dating is more widely used than any other method and radiocarbon ages are usually quoted for consistency. Approximate equivalent ages in calendar years BP are given in brackets.

Figure 13-2: Late-Pleistocene and Holocene events in Britain (after Ballantyne & Harris 1994); raised shorelines after Gray (1978) and Gordon & Sutherland (1993).

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The effects of the Quaternary ice ages on the topography are visible throughout the Inner Hebrides, the western Scottish seaboard and on Arran, with the formation of classic examples of U-shaped valleys, fjords, corries, arêtes, horns (pinnacle arêtes or pyramidal peaks) ((Figure 13-3; Figure 13-4; Figure 13-5; Figure 13-6; Figure 13-7; Figure 13-8; Figure 13-9; Figure 13-10; Figure 13-11; Figure 13-12; Figure 13-13; Figure 13-14; Figure 13-15).

These large erosional features began to form during earlier glaciations, but the glacial deposits preserved on and around the mountain massifs of Skye, Rum, Mull and Arran belong largely to the Main Late Devensian glaciation and were deposited during the Dimlington Stadial and in a subsequent, less extensive glaciation during the Loch Lomond Stadial (Figure 13-1; Figure 13-2). The mountains attracted high precipitation, and, under the prevailing cold conditions, this led to the formation of glaciers and local ice caps. During the Main Late Devensian glaciation these glaciers and ice caps coalesced into ice domes, which interacted with ice from much larger sheets on the Scottish Mainland (see below).



Figure 13-3: Classic glaciated terrain of the Cuillin, Skye, with corries, arêtes (ridges between corries), horns (pinnacle arêtes or pyramidal peaks) and tarns (in Coire Làgan and Coir' a' Ghrunnda). Note scree at the head of Coire Làgan, one of the dramatic 'stone chutes' that have formed due to efficient freeze-thaw action on minor intrusions within the Cuillin Intrusive Centre. Oblique Google Earth© Image. View towards the NE.

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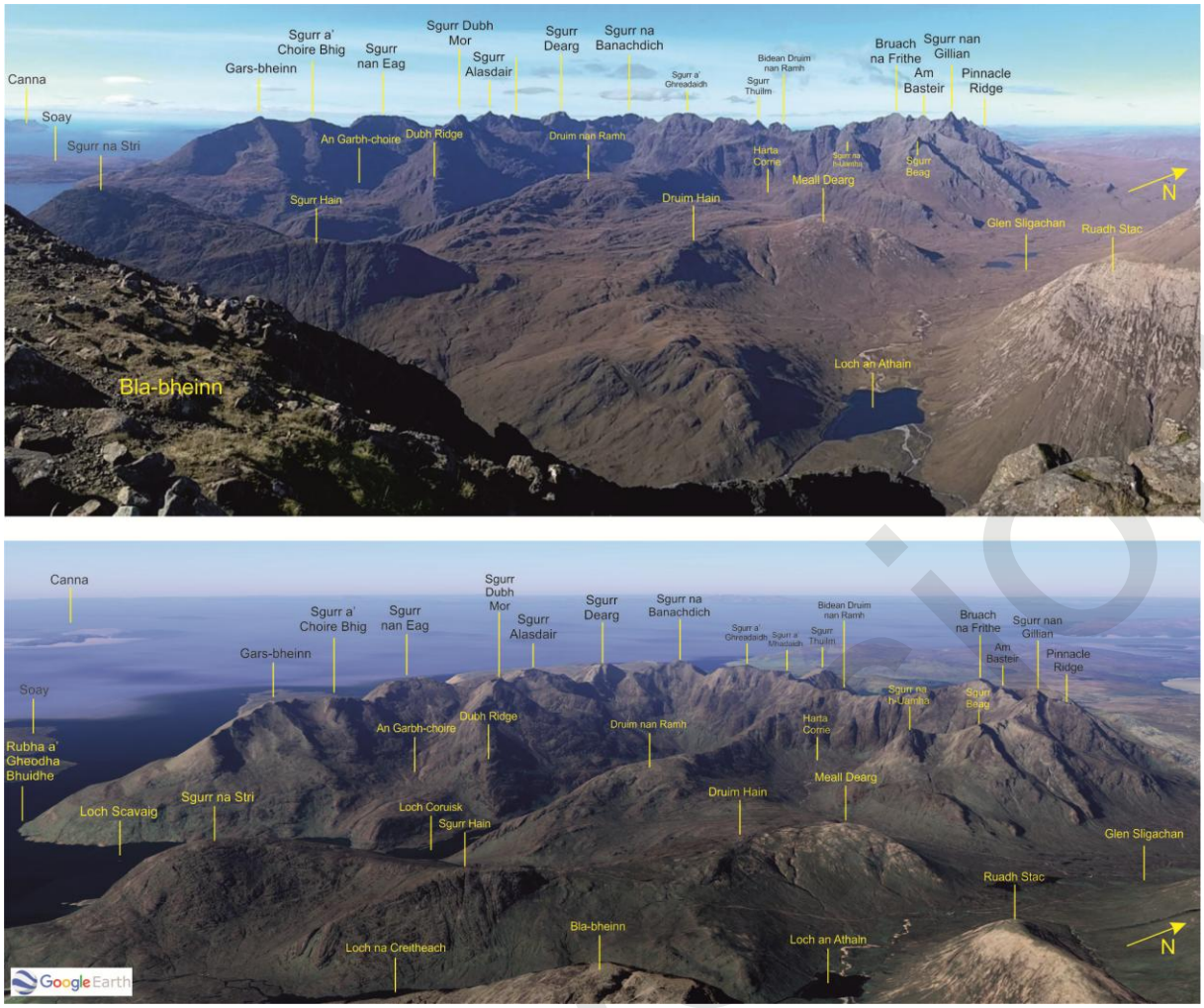


Figure 13-4: Field photograph (upper) and oblique Google Earth© image (lower) of the arc of the Cuillin, Skye, viewed towards the west from Blà Bheinn, with named summits (pinnacle arêtes, horns, or pyramidal peaks), ridges (arêtes) and corries.

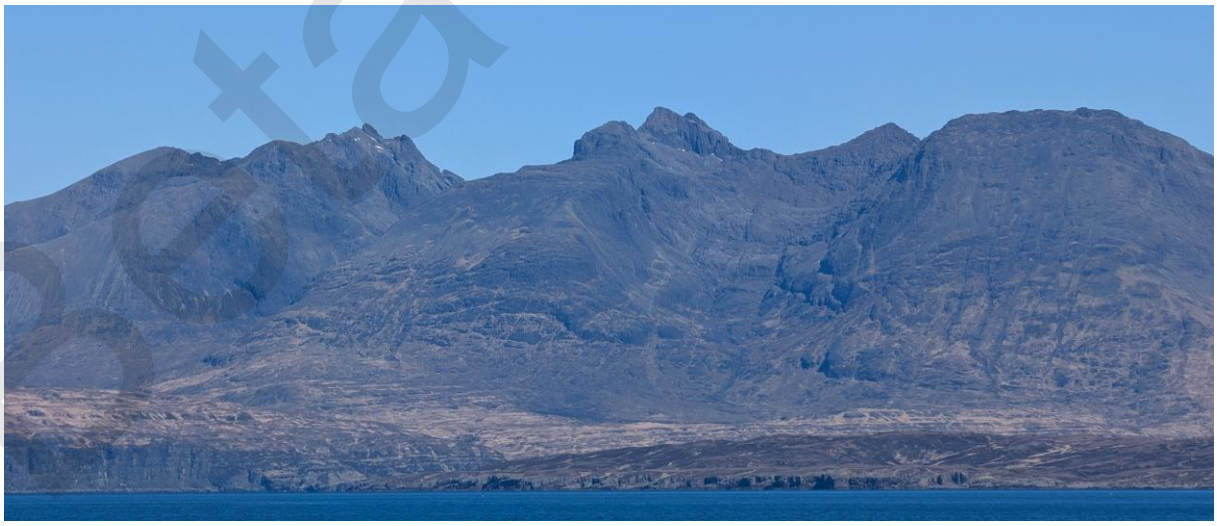


Figure 13-5: Glacially sculpted Coire Lagan (left) and Coir' a' Ghrunnda (right), southern Cuillin, Skye, from Soay.

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Figure 13-6: South Cuillin ridge (arête) separating the 'inner' corries (An Garbh-choire and Coire a' Chruidh) on the concave side of the ridge (left) from Coire nan Laogh on the convex side of the ridge (right). View towards the SE from Bealach a' Garbh-choire, with near summit of Sgùrr a' Choire Bhig and the distant summit of Gars-bheinn.

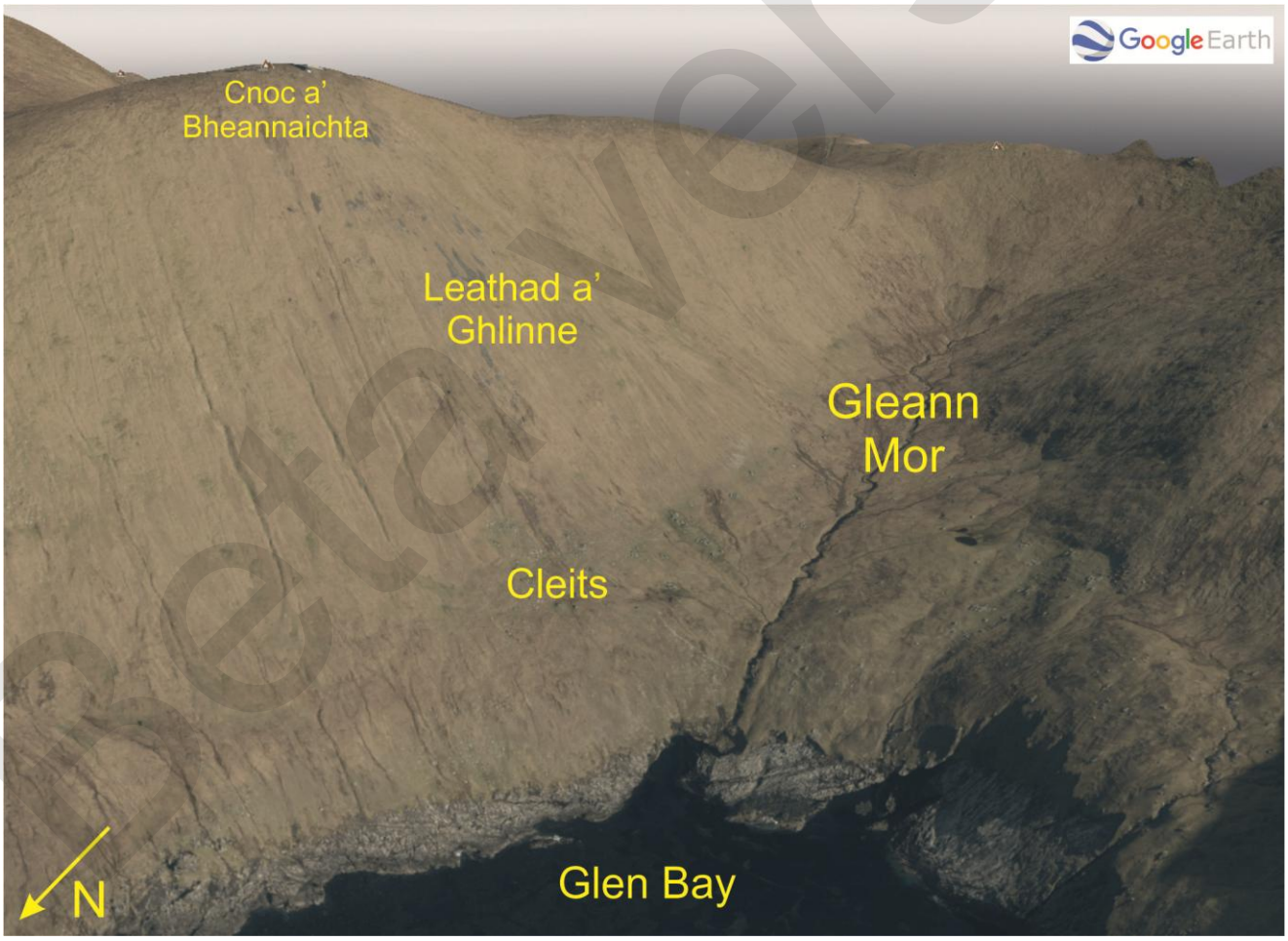


Figure 13-7: Gleann Mhòr, Hirta, St Kilda, a classic glacially formed U-shaped valley. View towards the south.

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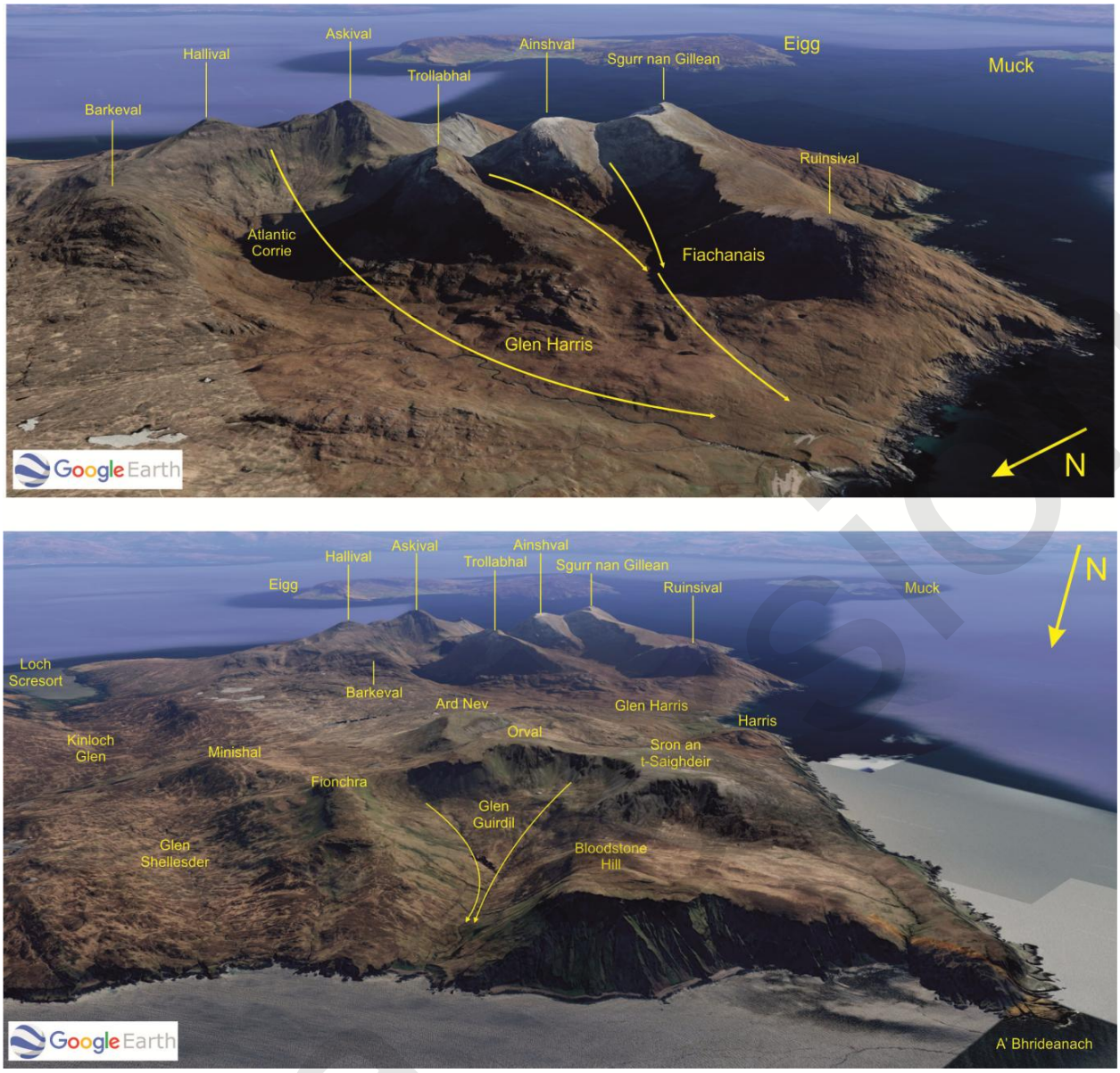


Figure 13-8: Classic glaciated terrain of west Rum, with corries, ridges (arêtes) and pinnacle arêtes (horns, pyramidal peaks). Oblique Google Earth© Image. Direction of ice flow in Glen Harris, Glen Guirdil and Fiachanais indicated.



Figure 13-9: Glaciated landscape of east Rum, with the twin summits of Askival (left) and Hallival (right). View towards the west. [Photograph courtesy of David Brown]

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Figure 13-10: The peak of Askival, Rum, and the ridge (arête) towards (right) Hallival. Below the arête is Coire nan Grunnd. View towards the SW. [Photograph courtesy of David Brown]



Figure 13-11: The peak of Hallival, Rum, from Askival, along the ridge (arête) towards north. In the far distance is the Cuillin of Skye. [Photograph courtesy of David Brown]

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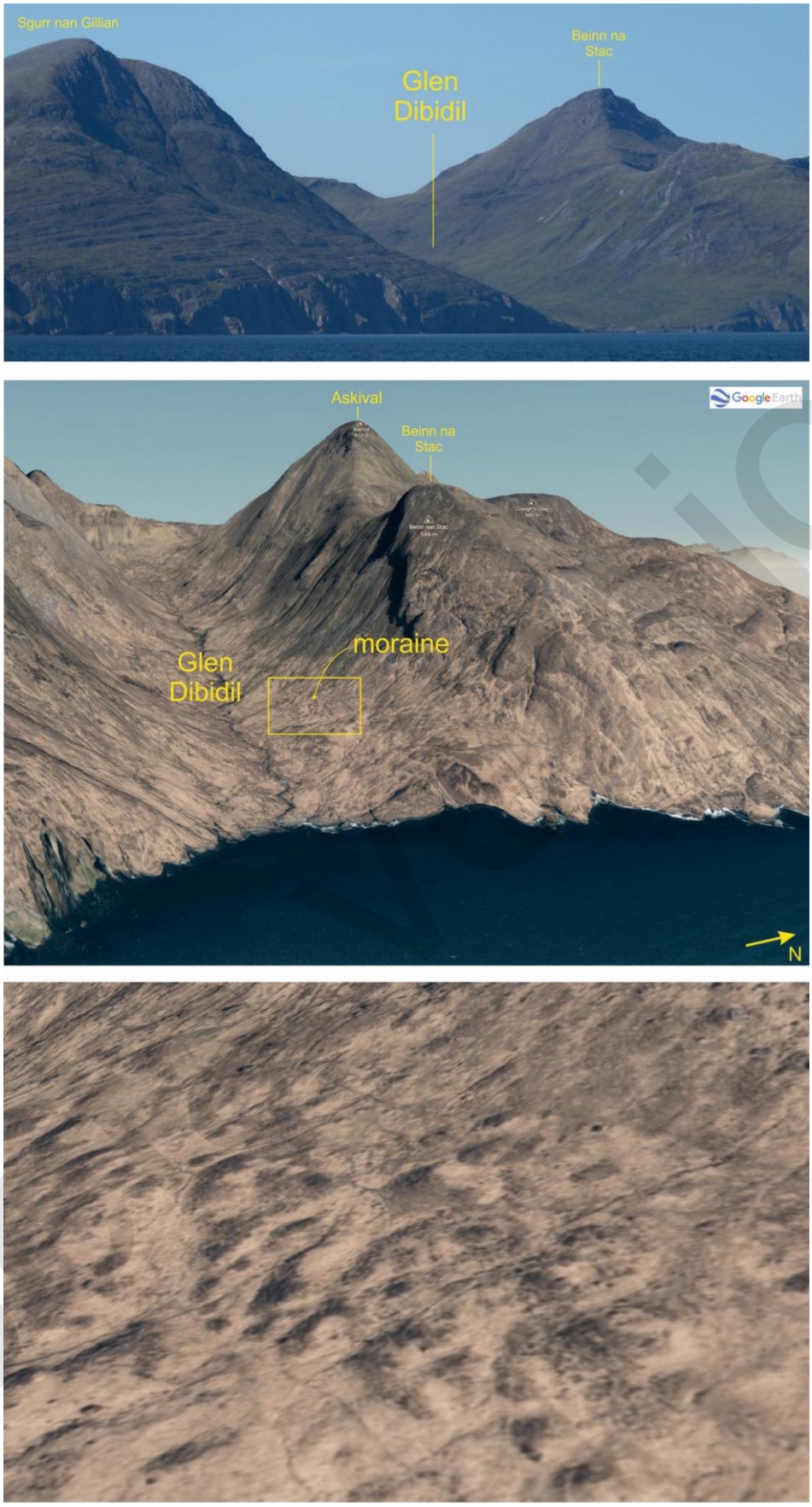


Figure 13-12: Field photograph (upper) and oblique Google Earth© image of Glen Dibidil, Rum, a classic glacially-formed U-shaped valley with patchily preserved moraine (lower image). View towards the NW.

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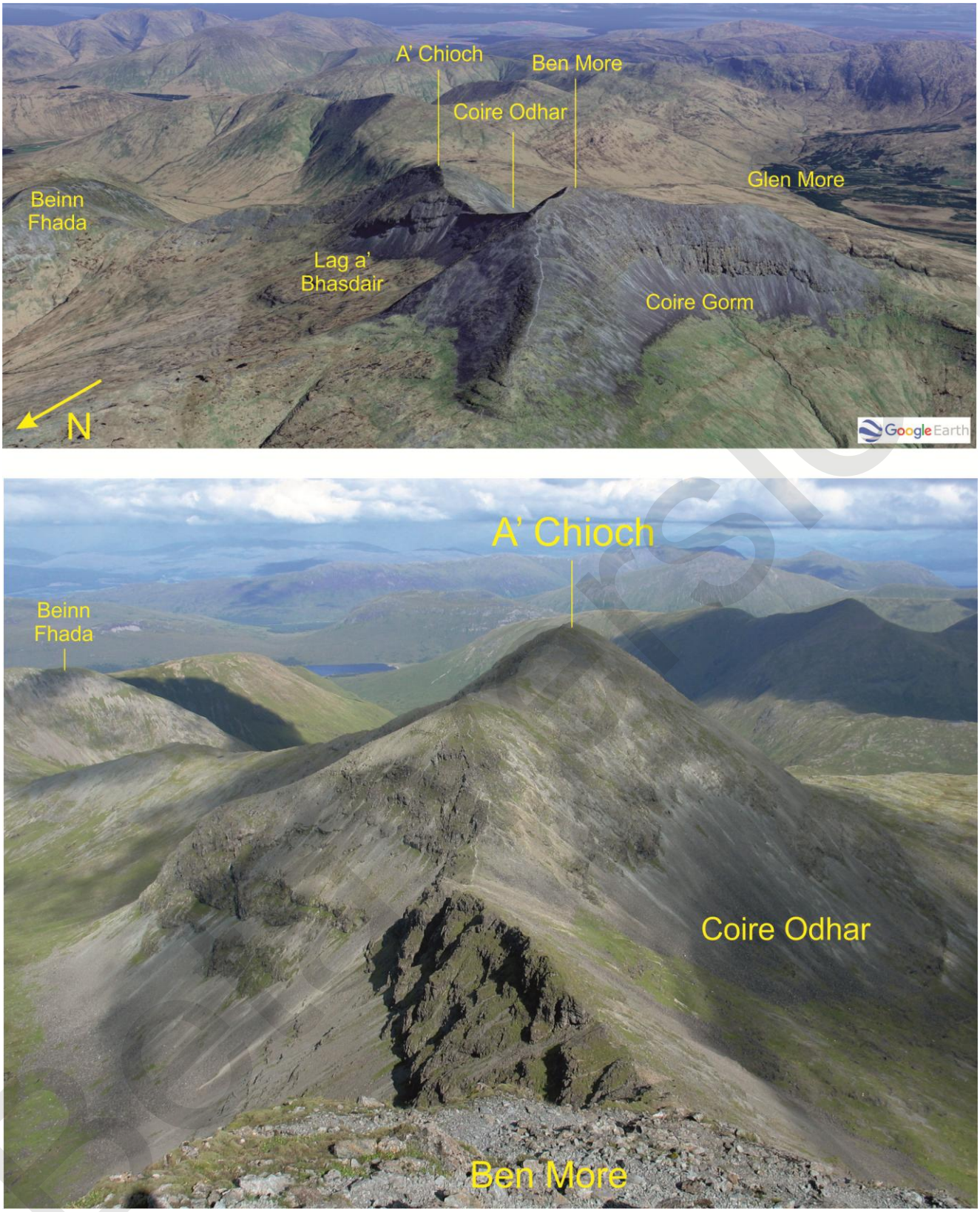


Figure 13-13: Oblique Google Earth© image (upper) towards the SE of the classic glaciated terrain of south-central Mull, with corries, ridges (arêtes) and horns (pyramidal peaks); and, field view (lower) towards the east from Ben More along the ridge (arête) to A' Chioch.



Figure 13-14: Glaciated pavement in the U-shaped Glen Rosa, Arran, with, in the distance, Cir Mhòr (right) and A'Chir (left of centre). View towards north.



Figure 13-15: Glen Rosa, Arran, a classic glacially formed U-shaped valley. View towards south.

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Figure 13-16: Coire Gorm, Strath, Skye. View east towards the Scottish Mainland.

Areas of hard bedrock with a moderate topographic range that have been sculpted by the action of ice commonly have rounded hills peppered with (commonly small) lochs, the so-called 'Cnoc and lochan' topography of Scottish literature (Figure 13-17). This type of topography of glacial origin is typical of large areas of NW Scotland.

The action of ice on bedrock produced glacial striae on ice moulded surfaces (roche moutonnées), together with crescentic scars that have the potential to act as ice flow indicators; trimlines define the upper limit of ice, above which rock is not striated but likely to show evidence of frost shattering (Figure 13-18; Figure 13-19; Figure 13-20; Figure 13-21; Figure 13-22; Figure 13-23; Figure 13-24; Figure 13-25; Figure 13-26; Figure 13-27; Figure 13-28; Figure 13-29).

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Figure 13-17: 'Cnoc and lochan' topography of Sleat, SE Skye, a Scottish term to describe glaciated areas comprising ice-sculpted hills ('cnocs') and small depressions occupied by water ('lochans').High ground of Sgiath-bheinn an Uird, composed of Cambrian quartz-arenite ('quartzite'), with Loch na Starsaich.

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Figure 13-18: Ice moulded quartz gabbro of Centre 2, Mam Clachaig, Mull [Photograph courtesy of John Faithfull]

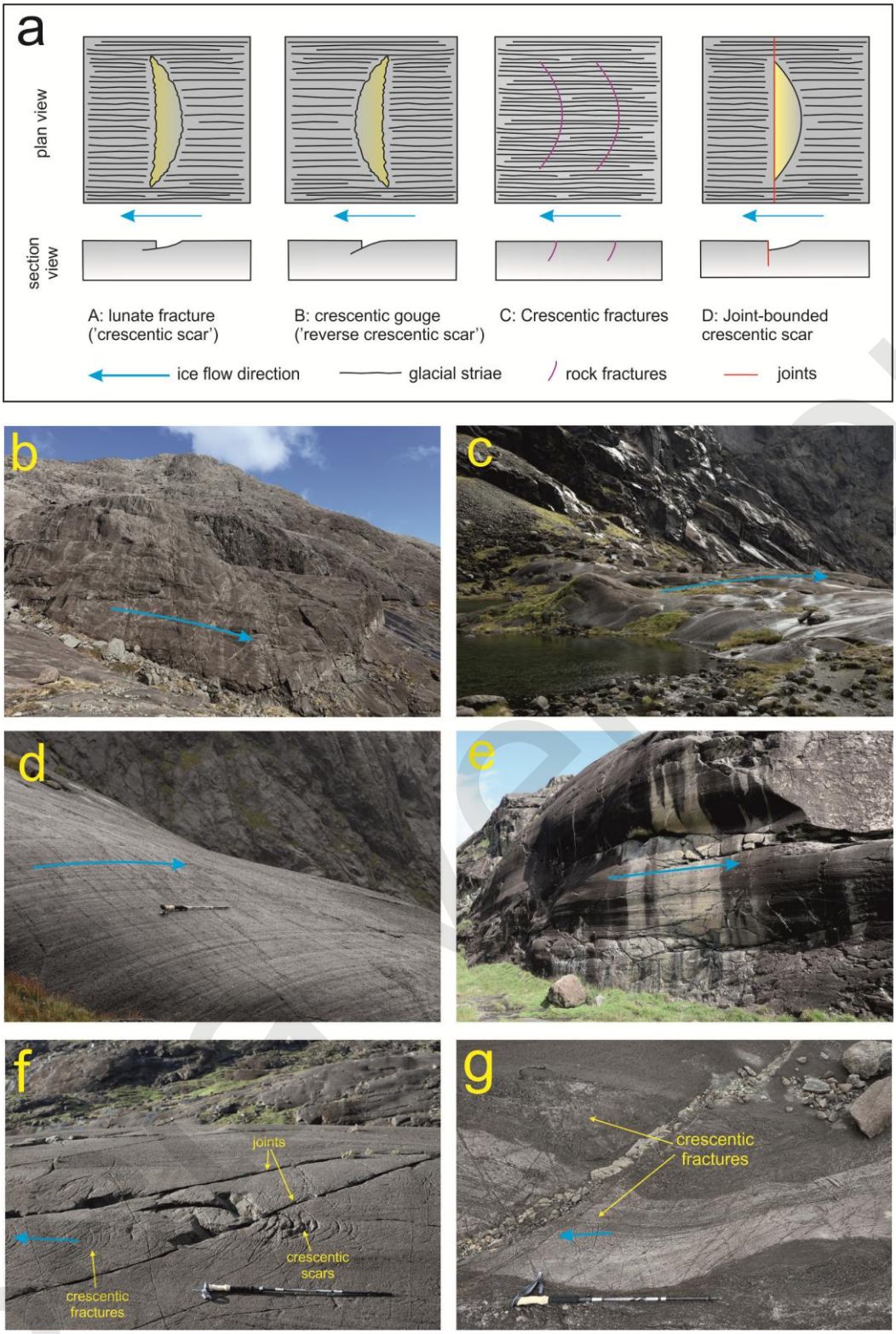


Figure 13-19: (a) Schematic of glacial striae, lunate fractures, crescentic gouges, crescentic fractures and crescentic scars; (b) near-vertical, glacially-excavated rockface on the SE side of Coir' a' Ghrunnda, giving way upwards through a trimline (vertical extent of last ice), above which the rock surface is mantled by loose blocks forming by freeze-thaw weathering; (c) ice-sculpted rock step or corrie lip in Coire Làgan; (d) glacial striae on a gabbro surface at the upper Coire Làgan rock step (or lip), pole *ca.* 1 m long; (e) glacial striae on a vertical surface of gabbro due east of the Coruisk Memorial Hut, west of the Scavaig River; (f) crescentic scars and fractures ('chattermarks') on gabbro surface, SW side of Loch Coruisk, pole *ca.* 1 m long; and, (g) crescentic fractures on gabbro surface, SW side of Loch Coruisk, pole *ca.* 1 m long. All views, Cuillin, Skye.



Figure 13-20: Crescentic scars and fractures ('chattermarks') on bytownite troctolite surface, Coir' a' Ghrunnda, Cuillin, Skye. Pole *ca*. 1 m long

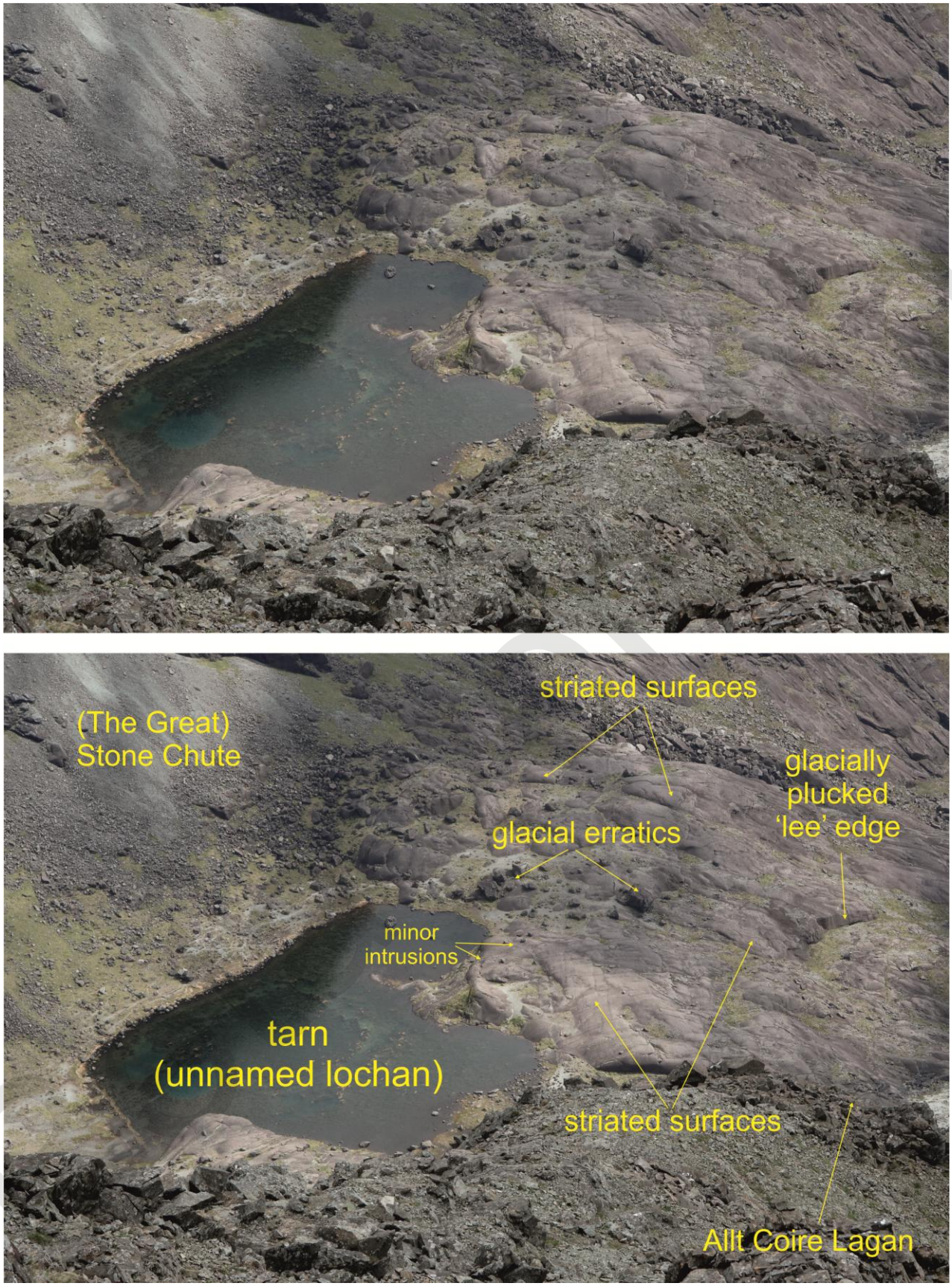


Figure 13-21: Glacial features of the area around the unnamed lochan in Coire Làgan, Cuillin, Skye, viewed from Sgùrr Dearg.



Figure 13-22: Glacial striae on an ice moulded gabbro surface at the upper Coire Làgan rock step (or lip), Cuillin, Skye.



Figure 13-23: Glacially moulded rock step or corrie lip, Loch Coir' a' Ghrunnda, SW Cuillin, Skye. View from Bealach a' Garbh-choire.

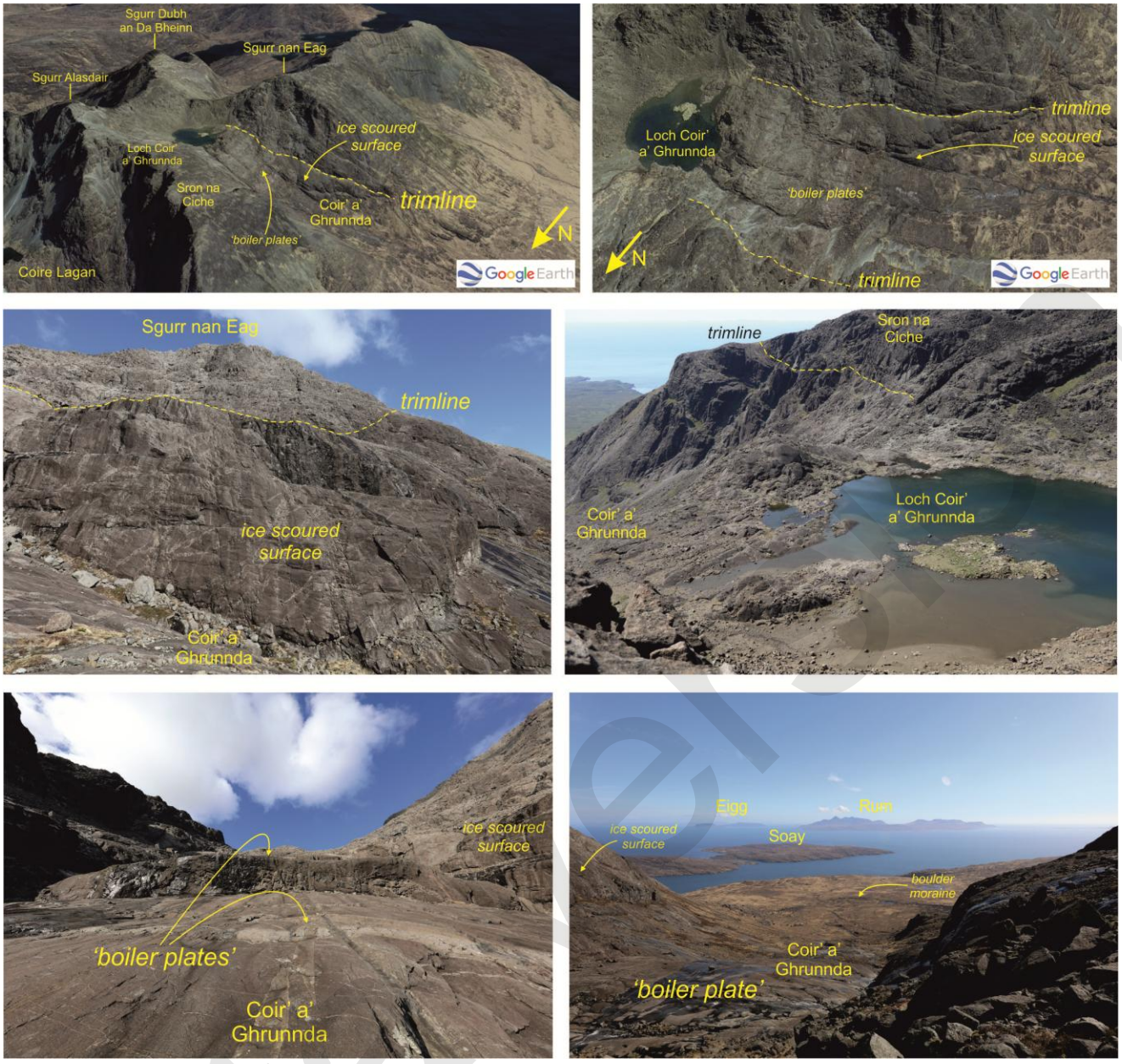


Figure 13-24: Annotated oblique and vertical Google Earth® images and field photographs illustrating glaciated surfaces ('boiler plates') and trimlines in Coir' a' Ghrunnda, Cuillin, Skye.

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Figure 13-25: Glacially polished Cambrian 'quartzite', Sgiath -bheinn an Uird, Sleat. Striae oriented bottom-left to top-right (E-W). Pole *ca.* 1 m long.



Figure 13-26: Glacially polished Cambrian 'quartzite', south of the Allt nan Leac valley, Strath. Coin *ca.* 24 mm across.



Figure 13-27: Glacial striae (parallel to pole) on the Beinn nan Dubhaich Granite, west of track adjacent to the Allt an Inbhire, between the head of the Allt nan Leac valley and Kilchrist, Strath. Pole *ca*. 1 m long.



Figure 13-28: Glacial striae on Dalradian Supergroup psammites, Rosa Water, Arran. Pole *ca.* 1 m long.



Figure 13-29: Detail of glacial striae on Dalradian Supergroup psammites, Rosa Water, Arran. Coin *ca.* 24 mm across.

Moraines (Latin, *Murrum,* rounded object), comprising poorly sorted rock debris (diamicton) left behind by a melting glacier, are widespread in glaciated terrains. Material that has been transported by glaciers is deposited during interstadials, resulting in a wide range of depositional features. Commonly used terms to describe certain of these deposits in Scotland are 'hummocky drift' or 'hummocky moraine', which perhaps describes their form, but not their mode of formation (Figure 13-30; Figure 13-31) (see below). The constituent materials can range from clay grade to boulders, commonly within one deposit. Stratification can range between being well developed and unstratified, or 'massive'.

Hummocky drift in the context of the Inner Hebrides represents a characteristic product of late-stage ice-sheet decay, formed primarily through the stagnation, downwasting, and melt-out of debris-rich ice during the Late Devensian deglaciation (McCann 1966; Sissons 1967, 1979; Boulton & Eyles 1979; Peacock 1984; Clapperton 1989; Peacock *et al.* 1992; Hall & Glasser 2003; Balantyne 2004, 2021; Evans 2009; Benn & Evans 2010) (Figure 13-1). It comprises irregular assemblages of mounds, ridges, 'kettles', enclosed hollows, and chaotic micro-relief underlain by poorly sorted diamicton, locally interbedded with sands and gravels (Figure 13-30; Figure 13-31; Figure 13-32). The morphology and sedimentology of these deposits record ice-sheet disintegration dominated by passive melt processes rather than sustained active retreat.



Figure 13-30: Hummocky moraine deposits north of Loch Fhuaran, SW Mull.

During the Last Glacial Maximum (LGM) (Figure 13-1), the Inner Hebrides were covered by a thick ice mass sourced from the Scottish Mainland and augmented by local ice caps centred on Skye, Mull, and Rum (see below). Ice flow was strongly topographically constrained by the Paleocene volcanic plateaux, deeply incised sea lochs, and structural lineaments. As climatic warming commenced after *ca.* 18,000 years BP, the ice sheet thinned rapidly. In many lowland and coastal areas, ice flow velocities declined, basal sliding

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became inefficient, and ice masses became detached from their accumulation zones. This led to widespread stagnation rather than organised retreat by active ice margins.

Hummocky drift formed predominantly in zones where ice stagnated *in situ*. These zones include coastal embayments, lee-side areas behind bedrock highs, and low-gradient terrain where meltwater drainage was inefficient. The stagnant ice contained large volumes of supraglacial and englacial debris derived from prolonged subglacial erosion of the basaltic and sedimentary bedrock, incorporation of pre-existing sediments, and repeated entrainment during earlier phases of ice advance. The volcanic lithologies of the Inner Hebrides contributed to high debris loads through mechanical disintegration and joint-controlled 'quarrying'.

As stagnant ice downwasted, debris was released progressively by melt-out. Differential melting exerted strong controls on landform development. Thick debris accumulations locally insulated underlying ice, retarding melting and forming positive relief as debris-covered ice cores persisted. Adjacent areas with thinner debris experienced more rapid melting, leading to surface collapse and the formation of hollows, kettles (see below), and enclosed basins. The resulting topography is chaotic and lacks consistent orientation, distinguishing hummocky drift from more 'streamlined' subglacial bedforms.

Sedimentologically, hummocky drift is dominated by massive to weakly stratified diamicton with a low degree of clast fabric development, reflecting passive deposition rather than deformation beneath actively flowing ice. Clasts are commonly angular to subangular, locally striated, and derived from nearby bedrock, indicating short transport distances. Abrupt lateral changes in lithology and grain size over tens of metres are common and diagnostic of melt-out deposition from heterogeneous debris sources within stagnant ice (Figure 13-33).



Figure 13-31: Unstratified moraine deposit with angular boulders of basalt, Loch Garbad, south Arran.

Preview version

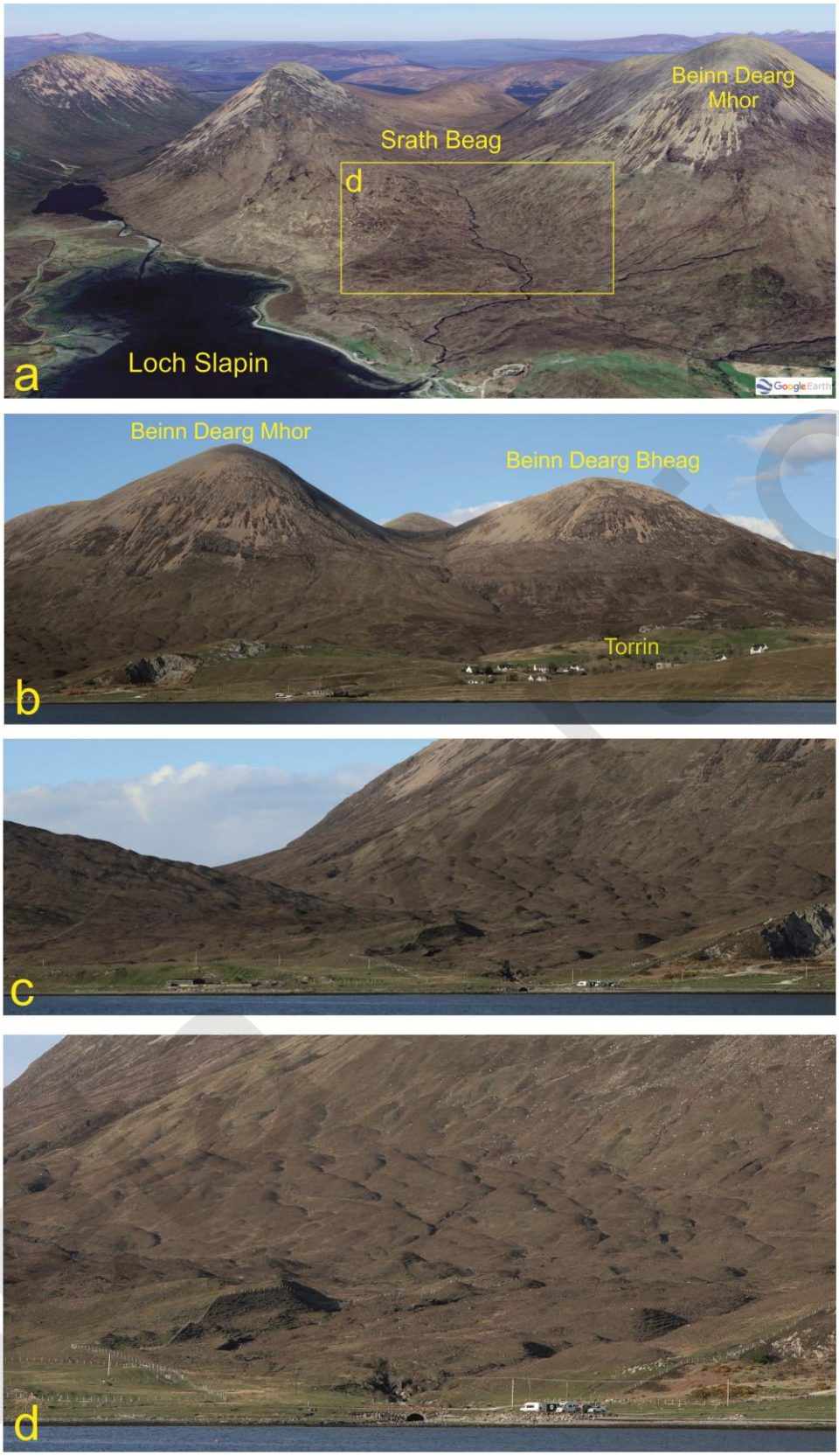


Figure 13-32: Oblique Google Earth© Image (a) and field images (b-d) of sub-glacially formed moraine deposits, at southern end of Srath Beag, Strath, Skye.

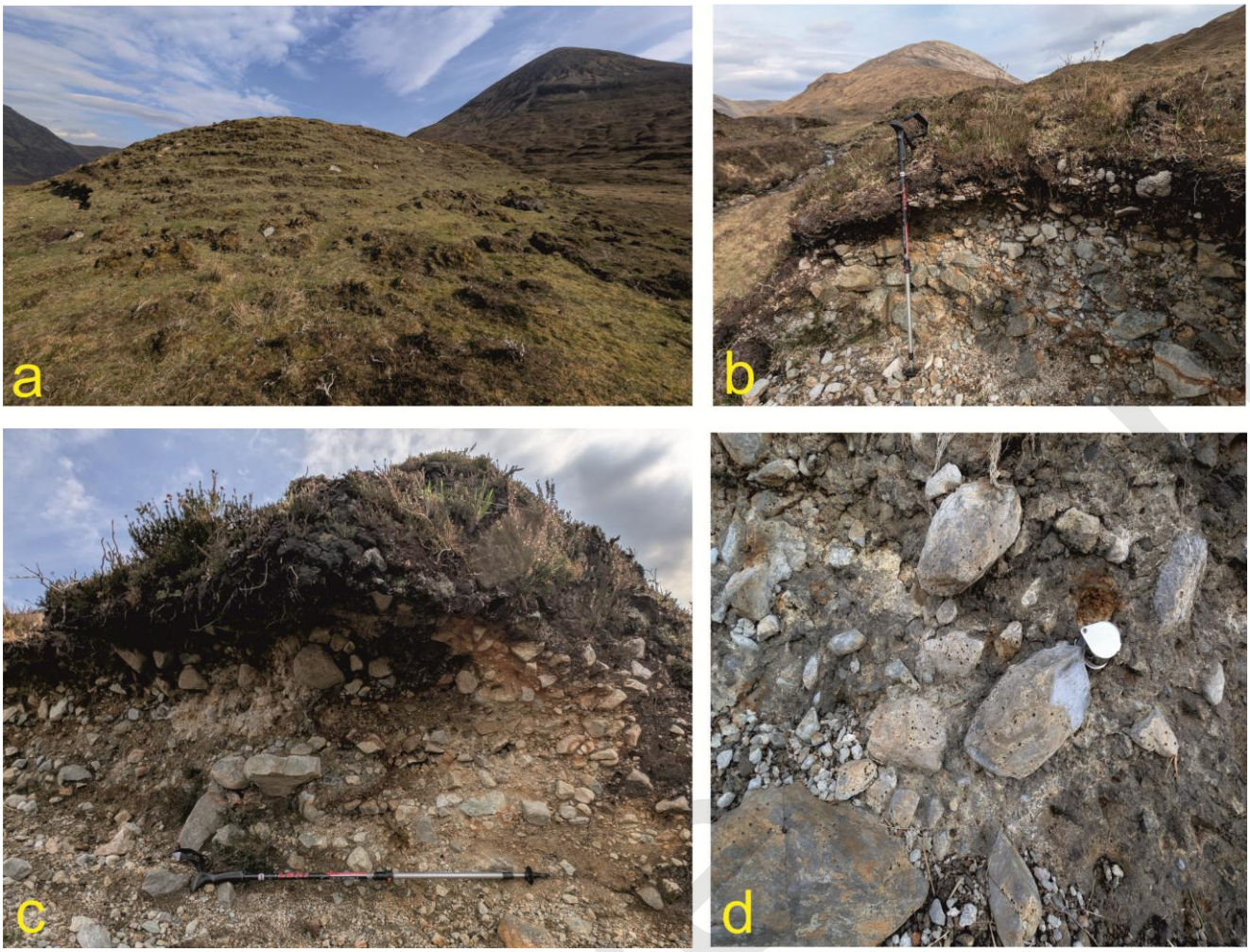


Figure 13-33: Field images of weakly to unstratified, sub-glacially formed moraine deposits ('hummocky drift'), at the southern end of Srath Beag, Strath, Skye. (a) illustrates typical 'exposure', (b, c & d) illustrate internal characteristics where exposed by recent erosion. Pole *ca*. 1 m long; hand lens *ca*. 6 cm long.

Meltwater processes played a subsidiary but locally important role in modifying hummocky drift. As ice decayed, meltwater was routed through ice-walled channels, englacial conduits, and supraglacial streams, reworking portions of the debris pile. This produced interbedded lenses of sand and gravel, short esker fragments, kame terraces, and ice-contact fans that are spatially intergrown with hummocky diamicton. These features do not form coherent outwash systems but instead accentuate surface irregularity, reinforcing the hummocky morphology.

Topographic and lithological controls strongly influenced the distribution of hummocky drift. On Skye and Mull, hummocky drift deposits are preferentially developed on low-lying coastal platforms, sedimentary basins, and gently sloping lava plateaux margins, where ice stagnation was prolonged. In contrast, upland areas and steep coastal escarpments show thin drift cover or streamlined till, reflecting more effective ice evacuation and meltwater flushing. The juxtaposition of hummocky drift with streamlined landforms over short distances records strong spatial variability in basal thermal regime and ice dynamics during deglaciation.

Chronological constraints place hummocky drift formation firmly within the Late Devensian, between *ca*.17 and 14 ka BP (Figure 13-1). Stratigraphic relationships with raised marine shorelines provide key temporal markers. In several coastal localities, hummocky drift is truncated by marine erosion surfaces or overlain by raised beach gravels associated with late-glacial or early Holocene relative sea level

stillstands. This demonstrates that hummocky drift predates shoreline stabilisation and records terrestrial deglaciation prior to full glacio-isostatic rebound.

The Inner Hebrides hummocky drift assemblages align with models of ice-sheet decay characterised by rapid thinning, surface lowering, and fragmentation into stagnant ice masses. Such decay contrasts with retreat by well defined, actively retreating margins and suggests that climatic warming outpaced the capacity of the ice sheet to maintain dynamic flow. The abundance of hummocky drift therefore provides evidence for ice-sheet instability during the terminal phase of the last glaciation.

The Hebridean examples of hummocky drift differ from examples elsewhere (for example, Arctic Canada, Scandinavia) by a strong lithological control, widespread association with raised marine features, and the influence of island-scale ice caps interacting with Scottish Mainland ice.

In summary, hummocky drift in the Inner Hebrides formed through Late Devensian ice stagnation and melt-out of debris-rich ice, modified locally by ice-contact meltwater processes and constrained by complex bedrock topography. Its morphology, sedimentology, and stratigraphic relationships provide critical evidence for the style and timing of Quaternary deglaciation in western Scotland.

Relative sea level changes resulted in modifications of the position of shorelines, caused by a reduction of the loading effects of ice on land and an increase in the volume of the oceans during interglacial periods (Figure 13-34; Figure 13-35; Figure 13-36; Figure 13-37; Figure 13-38).



Figure 13-34: Duart Castle, atop the Main Rock Platform (MRP) formed by sea level change, Duart Point, Mull.

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Figure 13-35: Main Rock Platform (MRP) formed by sea level change, Rubha nam Brathairean, Trotternish, Skye.



Figure 13-36: Raised shoreline, south of Dougarie, west Arran, possibly a combination of the Main Rock Platform (MRP) and a postglacial raised shoreline.

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Figure 13-37: Post-glacial raised beach at the foot of Late Glacial raised beach deposits at Harris, SW Rum. View towards the NE. [Photograph courtesy of David Brown]

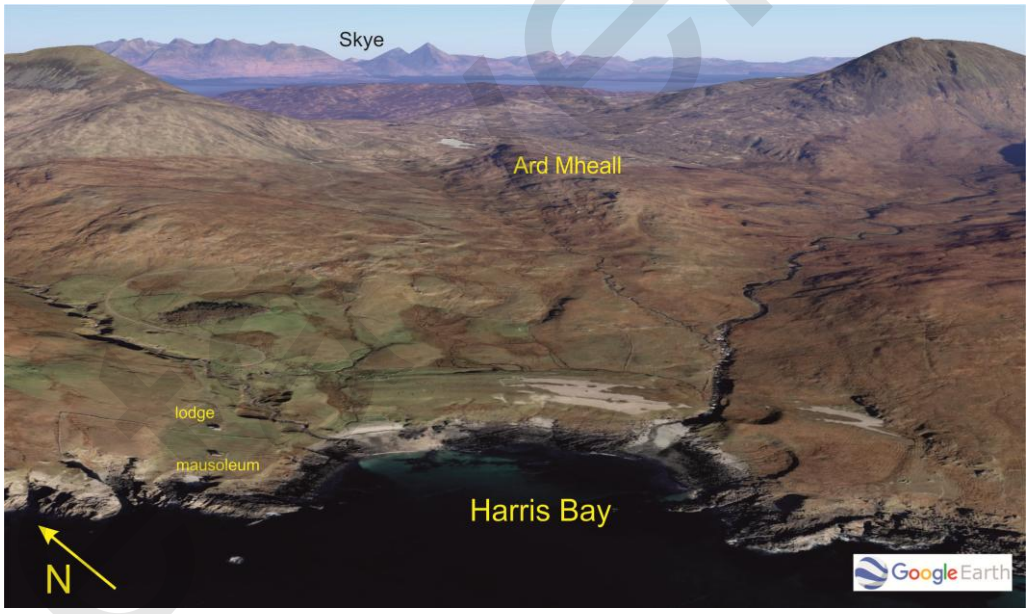


Figure 13-38: Oblique Google Earth© image of post-glacial raised beach at the foot of Late Glacial raised beach deposits, Harris Bay, Rum. View towards the NE.

As climatic conditions ameliorated, rocks that had been shattered by permafrost conditions over thousands of years were released and provided much surface detritus. Collapse of over-steepened glaciated valley walls was commonplace, and widespread landslipping and rock falls took place, both of which continue to the present day (Figure 13-39; Figure 13-40). Throughout the Inner Hebrides, landslips are especially common where thick successions of Paleocene lavas (Chapter 6) overlie incompetent Mesozoic sedimentary rocks (Chapter 3).



Figure 13-39: Landslipped blocks on the Trotternish Escarpment between Sgùrr a' Mhadaidh Ruaidh and Creag a' Lain, Skye. Note moraines at base of escarpment. View towards the SSW from Marishader.



Figure 13-40: Landslipped blocks, including the rock pillars of The Old Man of Storr (tallest, left) and Needle Rock (middle), on the Trotternish Escarpment east of The Storr, Skye. Note moraines at base of escarpment. View towards the south.

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By *ca*. 10,000 years BP, the climate had become more temperate, and the local glaciers and ice caps had melted. This change defines the start of the Holocene Epoch, formerly known as the Postglacial Period, and most likely another (as yet incomplete) interglacial. Soon after, Man reached the area.

Some of the earliest records of human activity in Scotland, of Mesolithic Age, come from Staffin, Skye, and from Rum where the local bloodstone (Chapter 14) was fashioned into artefacts at Kinloch. Radiocarbon determinations obtained from charcoal and from hazelnut shells from this site range from 8,590 ± 95 years BP to 7,570 ± 50 years BP (Wickham-Jones & Woodman 1998).

The Quaternary (Period) geology of the Inner Hebrides and Arran has been intensively studied over many years. The excellent field guides published by the Quaternary Research Association detail this research for specific areas and contain useful discussions of processes and descriptions of numerous key localities (Mull: Walker *et al*. 1985; Skye: Ballantyne & Lowe 2016; SW Highlands including Mull: Walker *et al*. 1992).

13.2 Early research on the Glacial and Post-glacial history of the Inner Hebrides

Research into and the acceptance of the evidence that the present-day landscape of western Scotland, including the mountainous areas of Skye, Rum, Mull and Arran, is strongly influenced by past glacial and related processes can be traced back to the pioneering work of James David Forbes, dating from 1836 though not published until 1845 (Forbes 1845). Cunningham (1990) has produced a detailed biography on Forbes, focussing on his studies on Scottish glaciers. Forbes embraced the theory of the Swiss American biologist and geologist, Louis Agassiz, that Earth had, in comparatively recent times, gone through Ice Ages and that abundant evidence is available for interpretation, in both the landscape and in surface deposits throughout the Inner Hebrides.

Evidence that convinced Forbes, based upon time spent in the area around Loch Coruisk in the Cuillin on Skye, includes glacial striae, ice-moulded bed rock, roches moutonnées and trimlines, together with various types of moraine (Figure 13-41; Figure 13-42; Figure 13-43; Figure 13-44; Figure 13-45; Figure 13-46). Other large-scale features, such as glacially sculpted corries, arêtes and horns (pyramidal peaks), were also interpreted as having a glacial origin. Observations were made in Coire Riabhach, NE of Sgùrr nan Gillean, in Coire na Creiche facing into Glen Brittle and, most compelling of all, in Coir' a' Ghrunnda, where the so-called 'boiler plates' of ice-moulded bedrock that form the stepped floor of the corrie give way, where it opens out into the open country to the SW, to a spectacular boulder moraine. In Coire Làgan, remarkable stone chutes below Sgùrr Alasdair were interpreted as the action of freeze-thaw processes.

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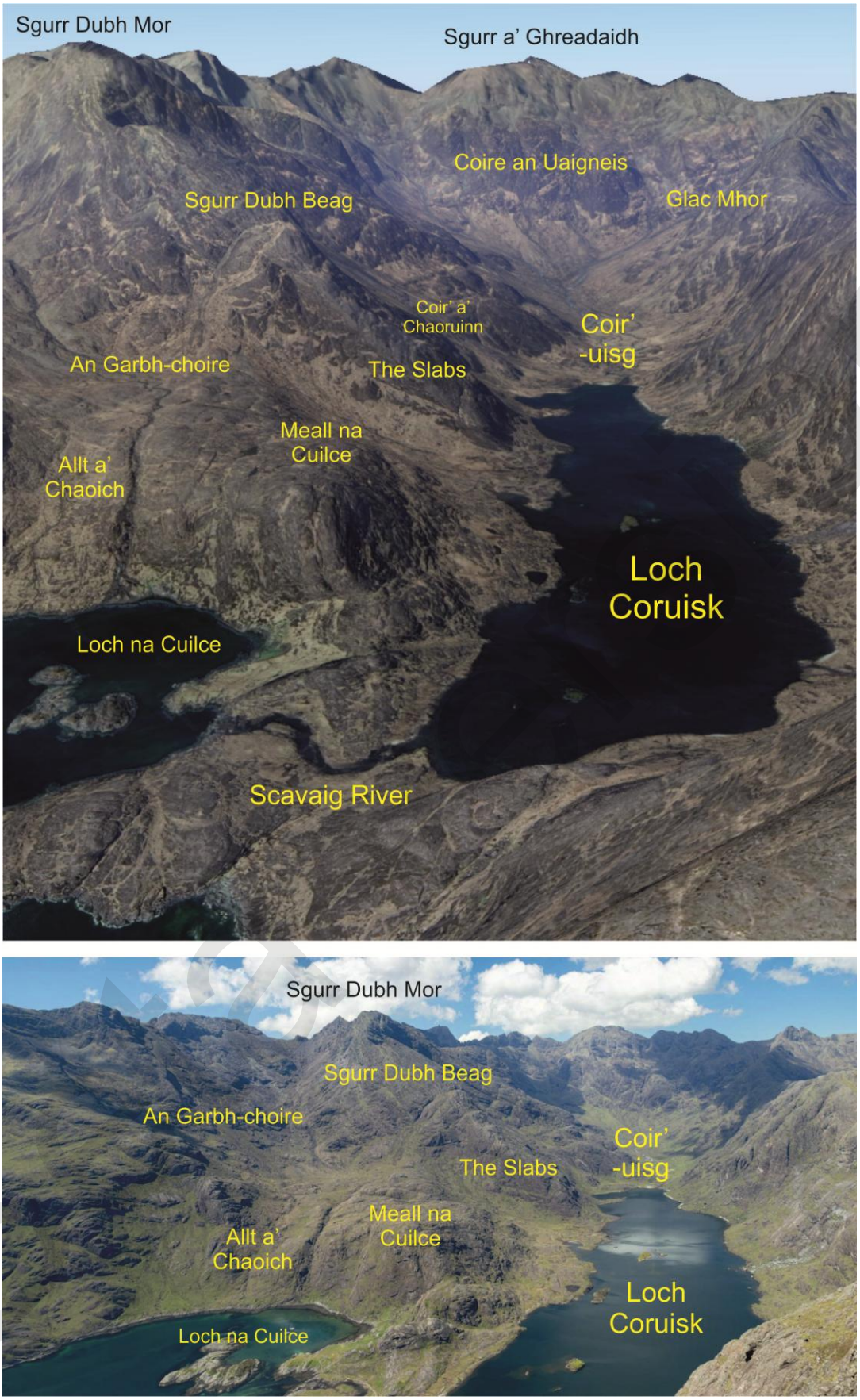


Figure 13-41: Annotated Oblique Google Earth© image and field view of the glacially sculpted Loch Coruisk basin, south Cuillin, Skye.



Figure 13-42: Glacial striae on an ice moulded gabbro surface, SW side of Loch Coruisk, Cuillin, Skye.



Figure 13-43: Horizontal glacial striae on the rock face behind the Coruisk Memorial Hut, Cuillin, Skye.



Figure 13-44: The Scavaig River, possibly the shortest river in Scotland, connecting the corrie-occupying freshwater Loch Coruisk (right) and the sea loch of Loch Scavaig (left), Cuillin, Skye. The ridge between the two lochs is a glacially moulded rock step or corrie lip. View towards west from Sgùrr na Stri.

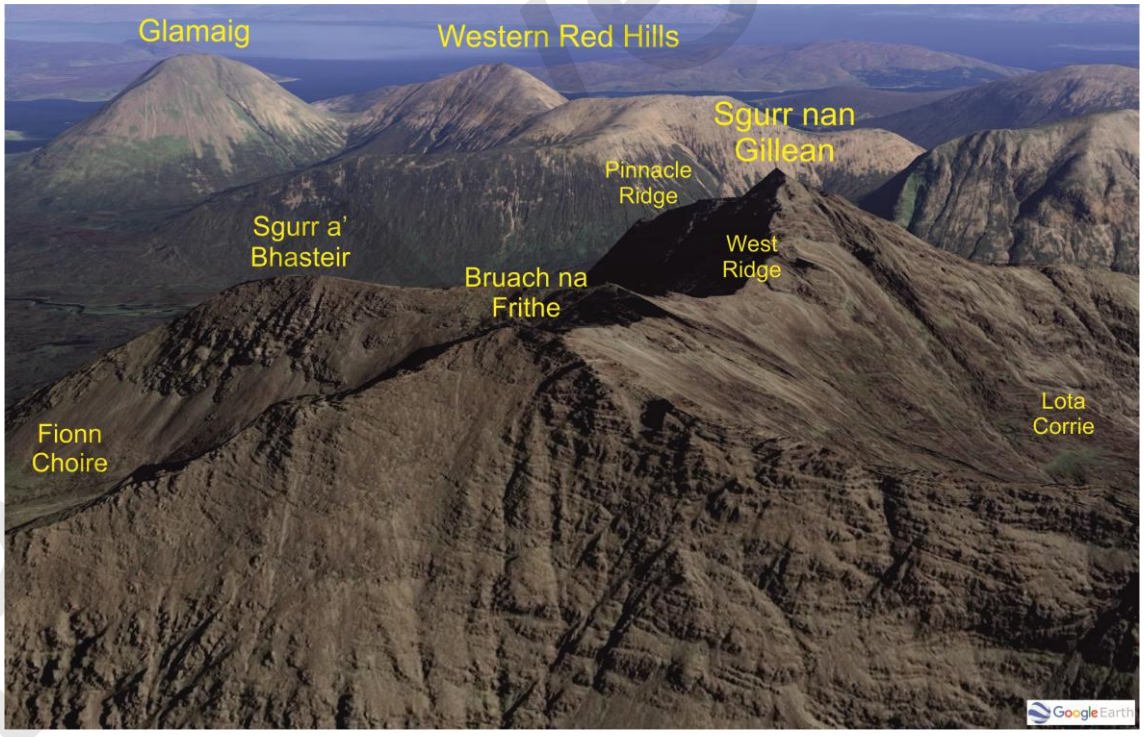


Figure 13-45: Oblique Google Earth© image illustrating arêtes and horns (pyramidal peaks) in the northern Cuillin, Skye: Bruach na Frithe (nearest) and Sgùrr nan Gillian (farthest). Radiating from Sgùrr nan Gillian are the Pinnacle Ridge, the West Ridge and the SE Ridge, all arêtes. In the distance are the granite-dominated summits of the Western Red Hills, including Glamaig. View towards the NE.

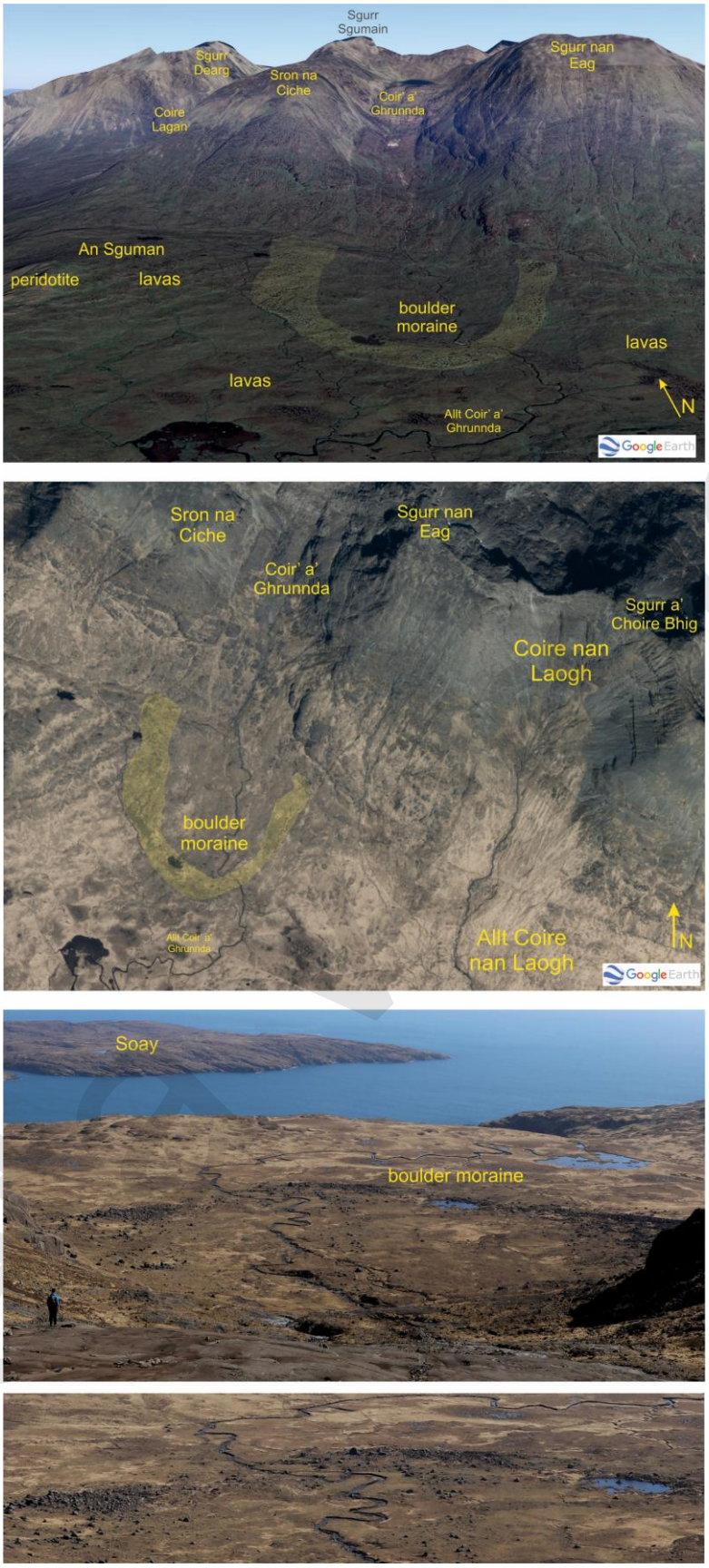


Figure 13-46: Annotated oblique and vertical Google Earth® images and field photographs illustrating the arcuate boulder moraine dominated by blocks of peridotite, troctolite and gabbro, where Coir' a' Ghrunnda, south Cuillin, Skye, opens out onto the vegetated plain of basaltic lavas, SW of the corrie.

Be

13.3 St Kilda

13.3.1 Early Local glaciations (Pre-Devensian)

Although Scottish Mainland British–Irish Ice Sheet (BIIS) reconstructions show extensive coverage of the Outer Hebrides and surrounding shelf sectors, St Kilda (Figure 13-47) was not overridden by the full BIIS during the Last Glacial Maximum (*ca*. 26 ka). Cosmogenic exposure dating on perched boulders at *ca*. 290 m OD yields ages averaging *ca*. 81.6 ± 7.8 ka, demonstrating that high ground on Hirta was not covered by the last ice sheet, which is consistent with St Kilda's ice-free status during major ice advances that reached near the shelf edge elsewhere (Ballantyne *et al*. 2017).



Figure 13-47:Annotated oblique and vertical Google Earth® image of St Kilda

However, local glacial activity did occur, most likely during earlier cold intervals in the Quaternary. Studies of drift sequences and tills exposed beneath the Ruaival and Village Bay areas on Hirta suggest the recognition of multiple cold stages, with the oldest identified glacial deposit, the Ruaival Till, interpreted as the product of an early local glaciation. This deposit is massive, up to *ca*. 20 m thick, composed of locally derived blocks and cobbles in a sandy-gravel matrix, and is exposed in the banks of the Allt Ruaival and below St Brianan's Church. Above it are stratified slope deposits interpreted as interstadial sediments, indicating at least one interglacial or warmer interval separating early glaciations (Harding & Nancarrow 1984).

These early glacial phases most likely represent cold periods in the Middle or Early Pleistocene, forming local valley ice or ice patches within depressions, rather than full ice cover, and may correlate with glacial events outside St Kilda where ice reached the Outer Hebrides.

13.3.2 Village Bay Glaciation (Late Devensian local glacier)

A second and more extensive glacial event, responsible for the Village Bay Till, is recognised throughout the low ground of Hirta. The Village Bay Till is more widespread than the Ruaival unit and is interpreted as having been deposited by a local corrie or valley glacier that flowed down into Village Bay during the Late Devensian. Though its precise age remains uncertain, this glaciation most likely occurred during the period commonly associated with maximum cold conditions in NW Britain (*ca*. 30–14 ka), when the Outer Hebrides Ice Cap fed ice streams into marine basins but, crucially, did not drive ice onto St Kilda itself (Hall 2021).

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The Village Bay Till comprises locally sourced blocks and sands, with internal structures consistent with subglacial or ice-contact deposition. The absence of widespread striated clasts and limited evidence of valley entrenchment suggest a cold-based, thin glacial system which may have been confined to higher ground and shaded hollows on the island.

13.3.3 Interstadial warm phase (Late Glacial)

Between the Ruaival and Village Bay tills is an interstadial horizon, where pollen-bearing sands accumulated. These organic sediments indicate a brief warmer interval between two glacial episodes, allowing vegetation to establish on otherwise cold barren ground before being overridden again. The presence of pollen in Gleann Mor infills and other local basins suggests open tundra or sparse shrub cover during this interstadial.

Although specific ages are lacking for the interstadial on St Kilda itself, regional correlations suggest this warm period most likely occurred during a Late Devensian amelioration phase prior to the final glacial deposition, possibly around *ca*. 20–17 ka BP, when interruptions in cold conditions permitted vegetation growth elsewhere in NW Scotland.

13.3.4 Lateglacial frost and blockfield development

A subsequent cold period late in the Late Glacial (13 0 - 14.7 ka BP) , following the deposition of the Village Bay Till and, prior to final ice melt, is characterised by extensive frost shattering of outcrops, development of blockfields, scree accumulations and protalus ramparts. This was a non-glacial periglacial stage associated with severe freeze–thaw cycles that extensively fractured the Western Gabbro and other igneous rocks (Chapter 9), particularly on steep faces such as Mullach Bi (Figure 13-48). The formation of scree and blockfields across Hirta's slopes reflects this late cold interval, which most likely corresponds with residual glacial conditions on the Scottish Mainland between *ca*.11 - 13 ka BP (Harding & Nancarrow 1984).

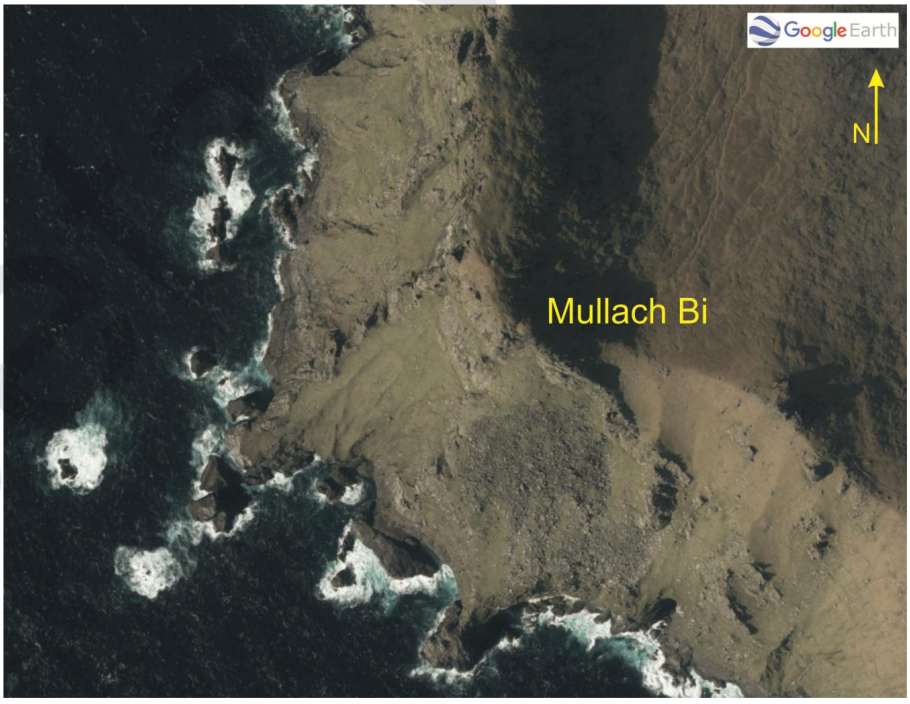


Figure 13-48: Frost shattered debris at Mullach Bi, Hirta, St Kilda.

Boundary version

Such frost activity would have produced thick blankets of angular debris downslope of cliffs, with protalus ramparts forming where snow and ice remained seasonally in shaded hollows, feeding debris at their margins.

13.3.5 Late Glacial sea level and marine platform development

Marine records and seabed mapping around St Kilda reveal submerged coastal landforms and platforms formed during episodes of lower sea level during the Last Glacial Maximum (LGM) and subsequent deglaciation. Nearshore platforms at a depth of *ca*. 120 m are interpreted as having formed during the LGM at *ca*. 15 ka BP, when global sea level was significantly lower and wave action cut into emergent bedrock. Shallower platforms between *ca*. 40–80 m depth may date to the Younger Dryas/Loch Lomond Stadial (*ca*. 11.5–13 ka), shaped by frost action and limited marine erosion before post-glacial drowning by rising sea levels (Alexandroff 2022).

These submerged platforms illustrate that, although St Kilda was not overridden by the BIIS, the coastal margins were significantly modified by marine processes working in concert with cold-climate influences.

13.3.6 Final deglaciation and Holocene landscape evolution

With the end of the Loch Lomond Stadial (*ca*. 11.7 ka BP), all ice on St Kilda melted, leaving a landscape of blockfields, scree slopes, and till remnants. Post-glacial relative sea level rise drowned coastal depressions, creating the present-day rugged, cliff fringed, coastline (Figure 13-49). There is no clear evidence of emergent raised beaches on St Kilda similar to those on the Outer and Inner Hebrides, suggesting either limited isostatic rebound or preservation below present sea level, in contrast to their development in more heavily rebounding parts of NW Scotland (Hall *et al*. 2021).

Holocene environmental records from pollen-bearing sediments indicate an early post-glacial tundra landscape, transitioning to grassland and heathland as the climate ‘warmed’. Later Holocene climate fluctuations, including the Little Ice Age (*ca*. 1400–1850 AD), are recorded in vegetation changes, but have left relatively minor physical geomorphological signatures compared to earlier glacial and periglacial phases.



Figure 13-49: The narrowing at Cleit, SE of Am Campar, Hirta, with Glen Bay to the left and the cliff highpoint of Mullach Bi to the right. [Photograph © Mick Crawley, licenced for reuse under Creative Commons Licence CC BY-SA 2.0]

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13.3.7 Summary of the Quaternary history of St Kilda

Early Local Glaciations (Pre-Devensian): Deposition of Ruaival Till by local glacier events, indicating multiple cold cycles;

Late Devensian local glacier (Village Bay Till): More extensive till deposition by local corrie/valley ice under cold climate;

Interstadial Warm Phase: Organic sediment accumulation between glacial episodes;

Late frost and blockfield development: Frost shattering and blockfield/scree formation during severe cold conditions;

Late Glacial marine platforms: Submerged platforms formed during lower sea levels at *ca.* 26–19 ka and stadial intervals;

Final deglaciation and Holocene evolution: Ice melt by *ca.* 11.7 ka, with post-glacial landscape stabilisation and vegetation succession.

13.4 Stages/chronology in Quaternary evolution of the Inner Hebrides

Six stages in the Quaternary evolution of the Inner Hebrides can be defined, albeit they are not discrete and are general. However, defining these stages is a useful aid to the understanding of the chronology of the glacial and glacially related Quaternary Period events. Details of these events are dealt with in more detail in subsequent sections.

13.4.1 Stage 1: Full ice-sheet glaciation (*ca.* 35-26 ka BP)

During the Last Glacial Maximum (LGM), much of the Inner Hebrides was enveloped by the British–Irish Ice Sheet (BIIS). Ice flowed radially from the Paleocene intrusive centres, such as the Cuillin on Skye, and the Paleocene lava sequence of Ben More on Mull, forming thick, warm-based ice caps. This extensive glaciation produced major erosional features, including fjords (Figure 13-50; Figure 13-51; Figure 13-52; Figure 13-53) and over-deepened glacial troughs, streamlined bedrock surfaces, and roches moutonnées. During this stage, the ice-sculpted landscape on Skye (for example, the Cuillin, Glen Sligachan and Loch Bracadale), Mull (Ben More, Loch na Keal), Rum (Rum Cuillin), and across the Small Isles, developed. The process was dominated by basal sliding, abrasion, and quarrying, which shaped the high-relief terrain and the deep marine embayments.

Beta version



Figure 13-50: Annotated oblique Google Earth® image of the glacially excavated Loch Scridain, SW Mull.



Figure 13-51: Annotated oblique Google Earth® image of the glacially excavated Loch na Keal, west-central Mull.



Figure 13-52: Annotated oblique Google Earth® image of the glacially excavated Loch Spelve, SE Mull.

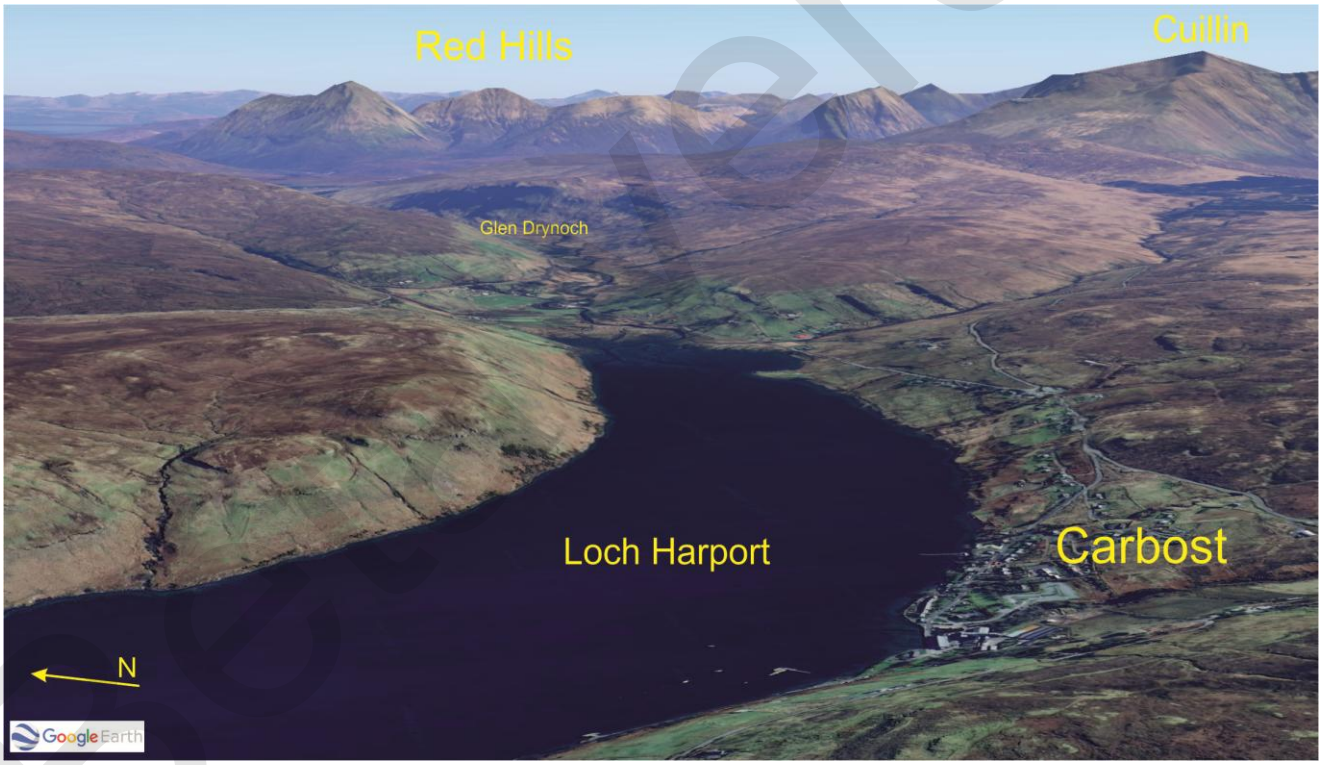


Figure 13-53: Annotated oblique Google Earth® image of the glacially excavated Loch Harport, west-central Skye.

13.4.2 Stage 2: Ice-sheet thinning and deglaciation (*ca*. 26-16 ka BP)

As climatic amelioration began, the ice sheet thinned and retreated dynamically, with stagnation on low ground and rapid calving in marine embayments. This phase produced hummocky moraines, thick drift

sheets, ice-contact gravels, and meltwater channels. On Skye, hummocky moraines and meltwater channels are evident in Strath, Broadford, and on Sleat, while on Mull, extensive drift sheets and ice-contact deltas formed around Loch Don and Loch Spelve. Rum preserves scattered till and glaciofluvial deposits, particularly near Kinloch, whereas the Small Isles preserve thin, patchy drift deposits. Retreat was often controlled by bathymetry, with overdeepened fjords accelerating ice loss.

13.4.3 Stage 3: Loch Lomond Stadial (Younger Dryas) glaciation (*ca.* 12-11.7 ka BP)

During the Loch Lomond Stadial, cold climatic conditions led to the formation of small, topographically constrained glaciers, primarily on Skye, Mull, and Rum. These glaciers occupied corries and upper valleys, producing end moraines, lateral moraines, drift limits, and valley glaciers. The Cuillin icefield on Skye is the most extensive, with outlet glaciers in Glen Brittle, Coire Làgan, and Coir' a' Ghrunnda. Rum's glaciers were confined to the Rum Cuillin (Askival, Hallival, Barkeval), while Mull hosted small plateau glaciers around Ben More. Eigg, Canna, and Muck remained unglaciated, although they experienced periglacial frost processes. The stadial landforms provide high-resolution records of Younger Dryas climatic conditions in a maritime context.

13.4.4 Stage 4: Periglacial/paraglacial slope adjustment (*ca.* 15-9 ka BP)

Following ice retreat, the landscape underwent periglacial and paraglacial modification, driven by freeze–thaw, solifluction, and stress release following ice unloading. Products include blockfields (felsenmeer), solifluction lobes and terraces, scree slopes, and large rock-slope failures or landslides. Skye features extensive blockfields on the Cuillin and Trotternish, with major landslides such as the Quiraing, The Storr, and Ben Tianavaig. Mull exhibits smaller landslides and solifluction terraces above Loch Bà and Carsaig Bay. On Rum, blockfields dominate high ridges, while the Small Isles show minor frost-shattered debris and solifluction deposits. This phase highlights the sensitivity of steep, newly deglaciated slopes to gravity-driven modification, reshaping upland terrains and supplying sediment to lower slopes and coastal systems.

13.4.5 Stage 5: Relative sea level change and coastal landforms (*ca.* 15-6 ka BP)

As ice-sheet retreat reduced local loading, relative sea levels rose due to eustatic change, then fell due to isostatic rebound, generating a sequence of emergent coastal features. These include raised beaches, wave-cut platforms, storm ridges, marine terraces, beach ridges, and deltas. On Skye, broad sequences exist in Broadford Bay, Loch Snizort, Kyleakin, and Loch Ainort. Mull preserves raised beaches at Loch Tuath, Loch Spelve, and Salen Bay. Rum shows storm ridges and gravel terraces at Harris and near Kinloch, while the Small Isles (Eigg, Canna, Muck) display emergent beaches such as Camas Sgiotaig and Camas Mòr. These deposits integrate paraglacial sediment supply from uplands, illustrating the interaction of ice-sheet inheritance with marine processes and storm activity.

13.4.6 Stage 6: Holocene stabilisation and modern processes (*ca.* 6 ka BP-present)

During the mid- to late Holocene, temperate conditions allowed vegetation colonisation, soil formation, and blanket peat development, stabilising slopes and limiting mass-movement activity. Products include blanket peat, soil mantles, minor debris flows, and the preservation of earlier Quaternary landforms. Skye

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features extensive peat, covering Trotternish, Minginish, Duirinish, Waternish, Strath and the low ground around the Cuillin, Mull has upland plateau peat over solifluction terraces, and Rum preserves blockfields beneath wet heath. The Small Isles maintain thin peat capping older deposits. Coastal modification continues today at cliffs and gravel beaches, but rates are slow compared with glacial and paraglacial activity. Holocene processes thus acted primarily to preserve earlier Quaternary evolution, shaping the modern, stable landscape of the Inner Hebrides.

13.5 Rock platforms in the Inner Hebrides: definitions and formation

Rock platforms in the Inner Hebrides form a stepped suite of erosional (palaeo) shorelines produced by marine planation under changing relative sea levels during the late Neogene Period (Pliocene Epoch) and Quaternary Period (Figure 13-54).

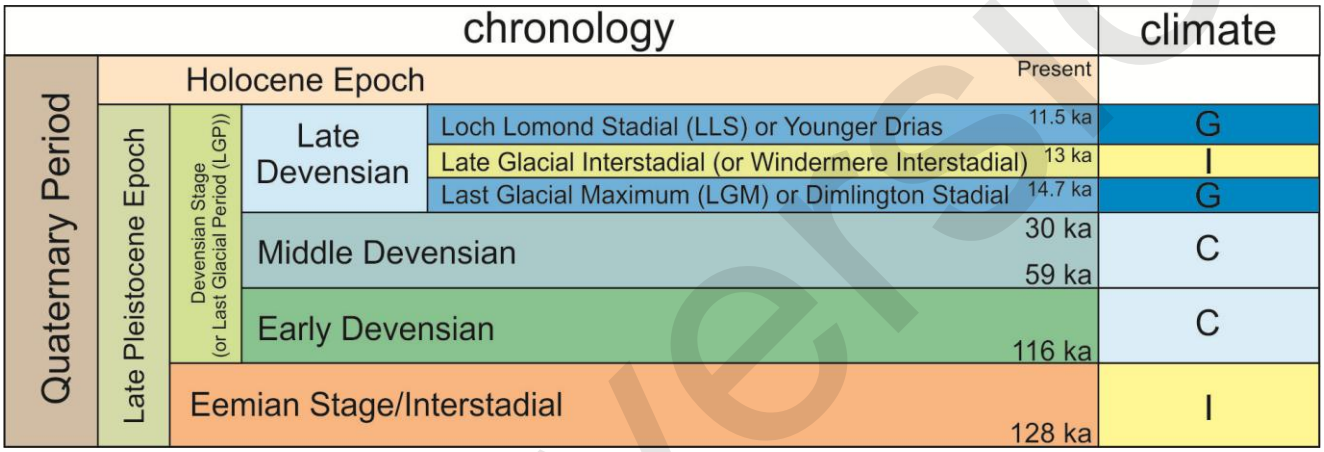


Figure 13-54: Subdivisions of the Quaternary Period. Climate conditions: G, glacial; I, interglacial; C, cold conditions, with possible glacial and interglacial periods. Subdivisions of the Quaternary Period. Climate conditions: G, glacial; I, interglacial; C, cold conditions, with possible glacial and interglacial periods. ka = thousand years.

Rock platforms, bedrock benches commonly associated with backing cliffs, are widespread around the Inner Hebridean islands. Sissons (1983) recognised three principal categories of rock platforms based on altitude, morphology, and inferred age: (1) low-level interglacial platforms; (2) a glacio-isostatically tilted Late Glacial rock platform (the Main Rock Platform, MRP, or Main Late Glacial Shoreline, MLS); and, (3) high-level rock platforms (High Rock Platforms, HRPs) at elevations exceeding *ca* 18 m OD. These categories reflect differing formative conditions, chronologies, and post-formational modification histories. There is still considerable debate concerning the validity of these subdivisions and the nature of their formation.

It should be noted that the near-horizontal, stratified nature of the Paleocene volcanic sequences which commonly fringe the islands of the Inner Hebrides (Chapter 6), in conjunction with the near-horizontal Paleocene sills of the Little Minch Sill-complex (Chapter 8) intruded into Jurassic strata (Chapter 3), have the potential to give a 'false signal' concerning the development of coastal benches.

Low-level platforms occur close to the modern tidal range and are typically fragmentary. They locally support glacially moulded bedrock outcrops and in places extend beneath till bluffs, indicating inheritance from earlier periods of coastal erosion. Dawson (1980a) interpreted these features as interglacial rock platforms that were subsequently modified by postglacial marine processes rather than

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being entirely Holocene in origin. Their close association with glacial deposits and moulded bedrock implies limited erosion during the last glaciation and preservation through ice cover or cold-based conditions.

The most extensive and regionally coherent feature is the Late Glacial rock platform, also termed the Main Rock Platform (MRP) or Main Late Glacial Shoreline. This platform is typically 50–150 m wide and is backed by cliffs 15–20 m high. It preserves relict sea stacks and arches, demonstrating formation by marine erosion after ice-sheet deglaciation. The platform typically reaches a maximum altitude of *ca*. 10–11 m OD in the Loch Linnhe area and eastern Mull, declining away from the centre of glacio-isostatic uplift in the Scottish Mainland at gradients of *ca*. 0.13–0.18 m km^{-1}. As a consequence of this tilting, the platform is preserved as an emergent shoreline in northern areas but occurs as an intertidal feature in southern Skye, eastern Rum, and southern Arran (Figure 13-55).

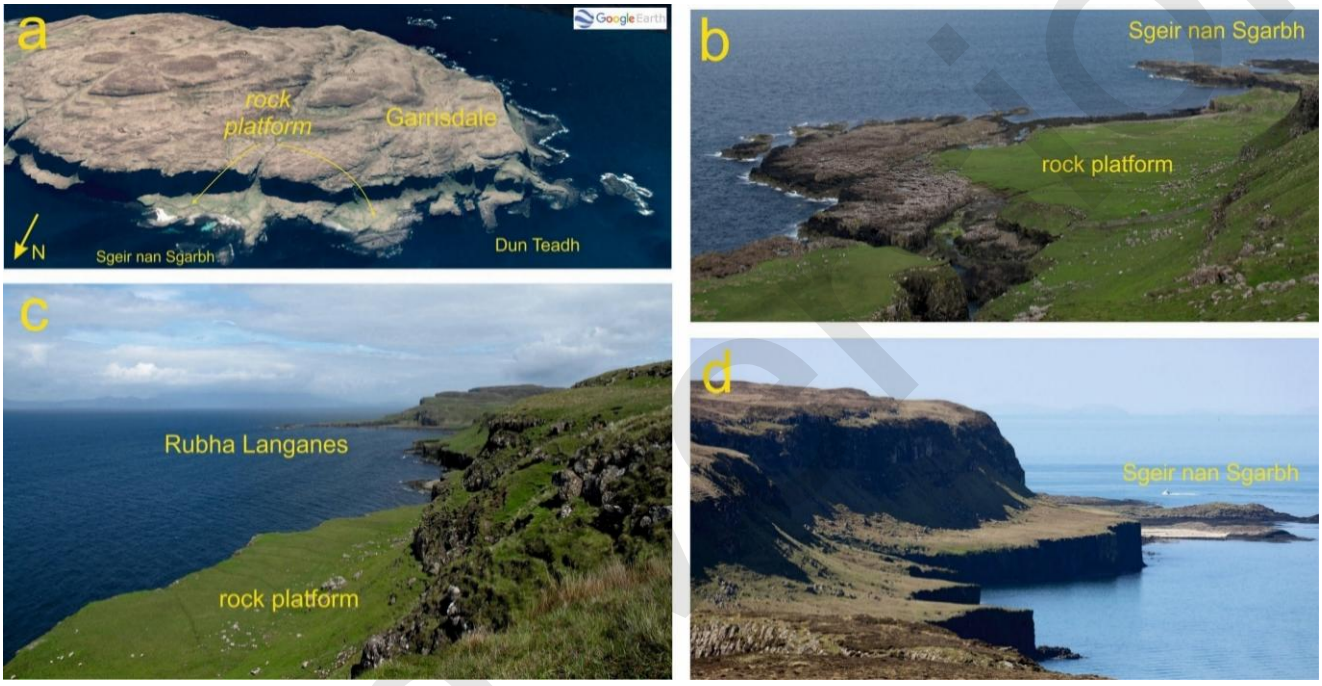


Figure 13-55: Annotated oblique Google Earth® image and field photographs of Late Glacial rock platform (or Main Rock Platform, MRP, or Main Late Glacial Shoreline, MLS), NW Canna.

The Late Glacial platform lies exclusively outside the limits of Loch Lomond Stadial glaciers and exhibits no evidence of glacial modification, implying formation after regional ice retreat. Its strong development in areas of limited wave fetch suggests that prolonged high-energy wave action was not required. Instead, it may have formed rapidly under periglacial conditions during the Loch Lomond Stade through the combined effects of frost-wedging of exposed bedrock and efficient removal of debris by storm waves and sea ice. This interpretation emphasises the importance of cold-climate mechanical weathering acting in concert with episodic marine processes. Abrupt vertical offsets of 1.0–2.7 m observed along the platform on Mull provide evidence for postglacial fault movement, indicating that tectonic activity has locally modified platform elevation.

High-level rock platforms (HRPs) constitute the most enigmatic group. These features are up to 700 m wide and are most extensively developed along the Atlantic-facing coasts of Islay and Jura, though narrower fragments occur along western Mull and NW Rum, where they extend discontinuously for several kilometres. Their altitudinal range spans from approximately 18 m to over 50 m OD, with variation between islands. Some higher fragments on Mull may represent lava benches rather than marine erosion surfaces,

Beta version

complicating interpretation (see above). In several areas, platforms at multiple elevations occur in close proximity, indicating that they do not represent a single former shoreline.

Evidence for glacial modification of high-level platforms is variable. Some fragments are ice-moulded or overlain by till, whereas others show no sign of glacial impact. Spatially, these platforms are confined to areas west of a line running through Skye, Mull, Jura, and eastern Islay (Figure 13-56; Figure 13-57; Figure 13-58; Figure 13-59). This distribution led Sissons (1982, 1983) to propose that they are fragments of intertidal rock platforms uplifted glacio-isostatically, formed during successive glacial periods when ice margins lay east of this line. Formation was attributed to frost action and storm-wave erosion under cold-climate conditions.

Alternative interpretations have been presented. Dawson *et al.* (2013) suggested that the HRPs may be remnants of a much older, Pliocene strandflat surface - a wide relatively planar bedrock surface extending from the shore both above and below sea level - that was subsequently modified by glaciation and uplift. A further possibility is that some HRPs formed during retreat of the last ice sheet. Cosmogenic nuclide dating indicates a *ca.* 3000 year interval between approximately 20 and 17 ka BP when an oscillating ice margin occupied the Inner Hebrides (Small *et al.* 2017). Palaeo-tidal modelling suggests mega-tidal conditions during this period, favouring intense coastal erosion and rapid removal of frost-generated debris. Ice-margin oscillation provides a plausible explanation for the mixed evidence of glacial modification observed on high-level platform fragments.

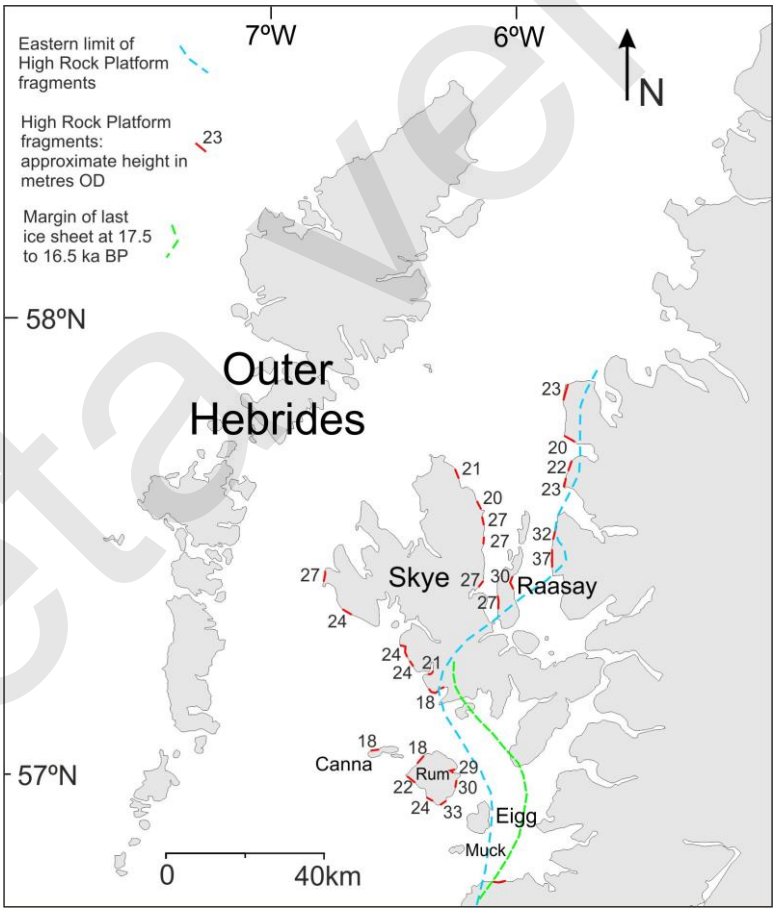


Figure 13-56: Distribution and approximate altitudes (m OD) of (some, but most likely not all) fragments of High Rock Platforms (HRPs) in the northern Inner Hebrides (after McCann 1968; Richards 1969; Sissons 1982; Small *et al.* 2017; Ballantyne 2021).

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Figure 13-57: High Rock Platform (HRP) at Neist Point (Rubhan a h-Eist), Duirinish, west Skye. View towards the SW.

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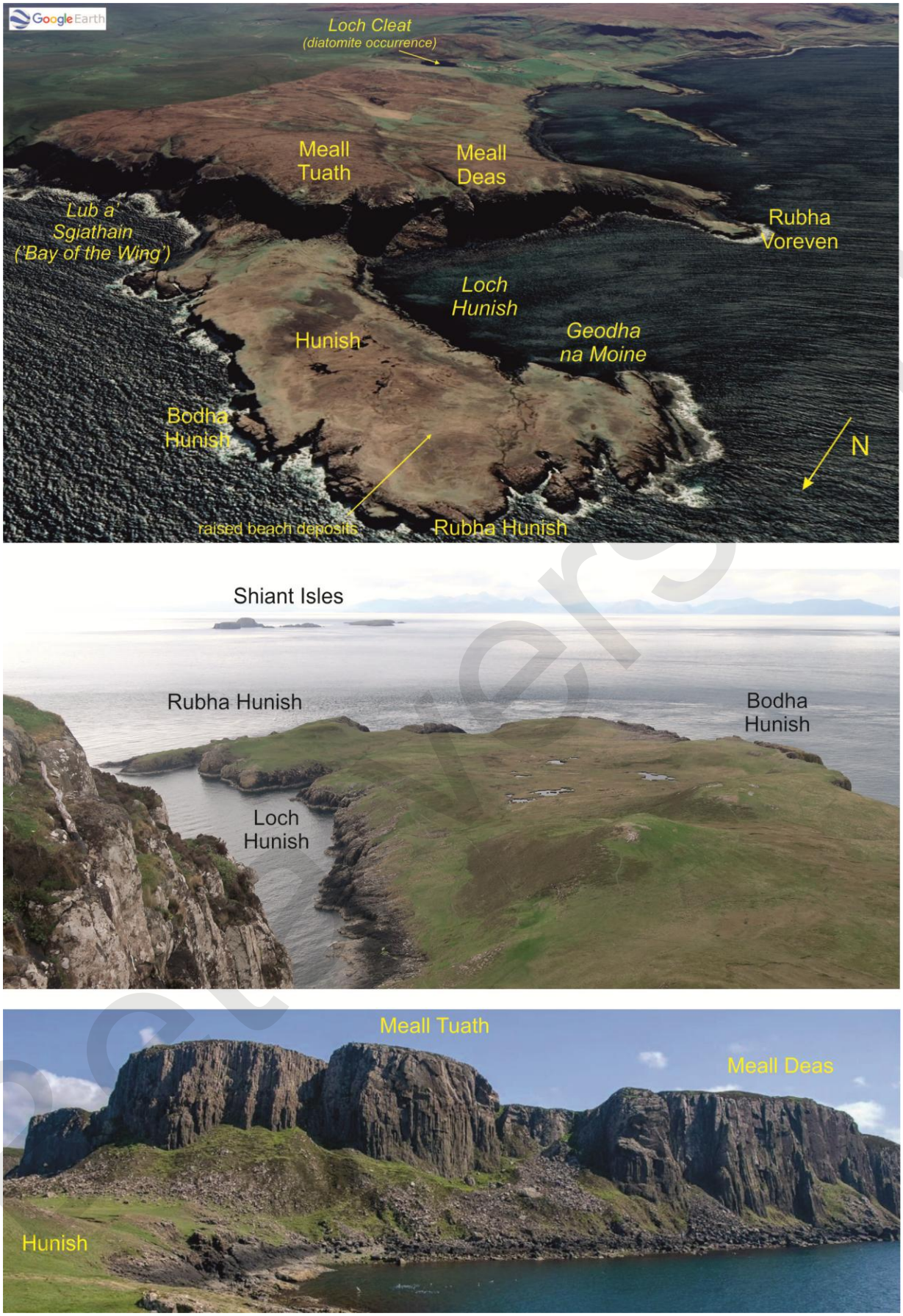


Figure 13-58:High Rock Platform, Rubha Hunish, Trotternish, Skye.



Figure 13-59: High Rock Platform (HRP) and relict solifluction sheets and lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age, Rubha na h-Uamha (at the Macculloch's Tree lava section), Ardmeanach, SW Mull.



Figure 13-60: High Rock Platform (HRP) and relict solifluction sheets and lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age, Coireachan Gorma section, Ardmeanach, SW Mull.

Pre-publication version

13.6 Dimlington Stadial: Main Late Devensian Glaciation

The extent of former glaciers has been deciphered by establishing the source of glacial erratics in the tills and moraines, and by recognising glacial trimlines. Trimlines define the highest levels to which glacier ice has actively eroded, or trimmed, frost-shattered bedrock and debris (blockfields, or felsenmeer (German: 'sea of rock')) on protruding peaks (nunataks, Inuit: 'lonely peaks') (Figure 13-61; Figure 13-62; Figure 13-63). Above the trimline, frost-shattered bedrock will persist but on the lower slopes, below the trimline, the bedrock will be glacially moulded and striated; it defines a transition in ice thermal regime (Figure 13-64).

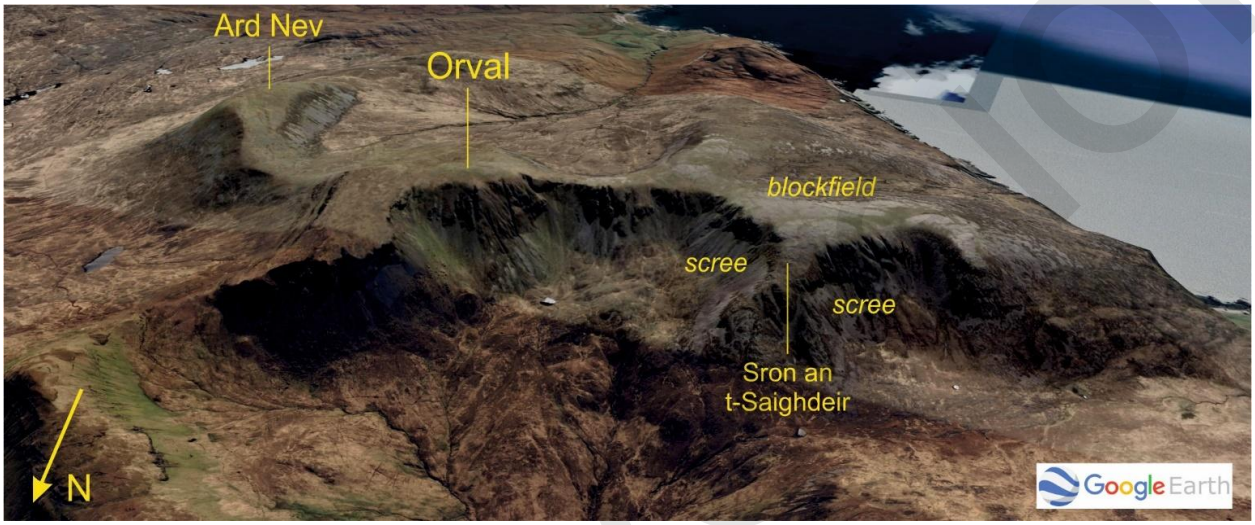


Figure 13-61: Oblique Google Earth© image of blockfield (felsenmeer) mantling the outcrop of the Western Granite on Orval, Rum.



Figure 13-62: Blockfield (felsenmeer) mantling the outcrop of the Western Granite on Orval, west Rum. In the distance are the summits of east Rum, composed of various basic and ultrabasic rocks of the Paleocene Rum Central Complex.

Data version



Figure 13-63: Fionna-choire and Coire Uaigneich, Skye, viewed towards the NE. The upper part of Fionna-choire is dominated by a blockfield or felsenmeer, formed by frost action on the granite. In the distance are the (Eastern) Red Hills of Strath.

Below the trimline, terrain overridden by warm-based ice commonly preserves glacially transported boulders and other depositional products, reflecting ice erosion and sediment redistribution. In contrast, nunataks above the trimline typically preserve thick accumulations of frost-weathered debris and blockfields, as cold-based ice or ice-free conditions resulted in minimal erosion and little removal of pre-existing regolith (Figure 13-64; Figure 13-65; Figure 13-66; Figure 13-67; Figure 13-68; Figure 13-69; Figure 13-70). The mineralogy of weathered materials may differ; gibbsite is common in the clay fraction of debris on former nunataks but is rare, or absent, below the trimlines. Subsequent events may obscure or eliminate the evidence of trimlines, for example the downslope movement of scree debris (Ballantyne 1997, 1999, 2021).

Beta version



Figure 13-64: Glacial erratics sitting on striated, glacially moulded bedrock (gabbro) close to the SE end of Loch Coruisk, Skye. View towards the NW.



Figure 13-65: Glacial erratics sitting on striated, glacially moulded bedrock in the Loch Coruisk basin, Skye.

Boa ver



Figure 13-66: Glacial erratic, Kinloch Glen, Rum



Figure 13-67: Glacial erratics at Am Màm, Skye, south of the Kilmarie-Camasunary footpath. View towards the south.

Draft version



Figure 13-68: Glacial erratic of granite, Clach a' Chath (Cat Stone), between Corrie and Sannox, NE Arran.



Figure 13-69: Glacial erratics of granite between Corrie and Sannox, NE Arran.

Pre-version



Figure 13-70: Glacial erratics of granite in Glen Rosa, north Arran, with the glacially sculpted Cir Mhòr, and beyond.

During the early to main phases of the Late Devensian, the Inner Hebrides and Arran were almost entirely overridden by the British–Irish Ice Sheet (BIIS). Ice extended west of the Inner Hebrides onto the continental shelf, but probably did not reach St Kilda, which instead supported local ice caps and valley glaciers (see above). Prior to full ice-sheet expansion, and again during deglaciation, mountainous terrain in the Inner Hebrides favoured high snowfall and the development of local glaciers under cold climatic conditions. During the Main Late Devensian, however, these local glaciers were subsumed by a thick regional ice sheet, within which ice divides and domes developed as a function of ice-sheet thickness and flow dynamics. Ice flow across the islands was strongly influenced by interaction with much larger ice masses centred on the Scottish Mainland (Figure 13-71).

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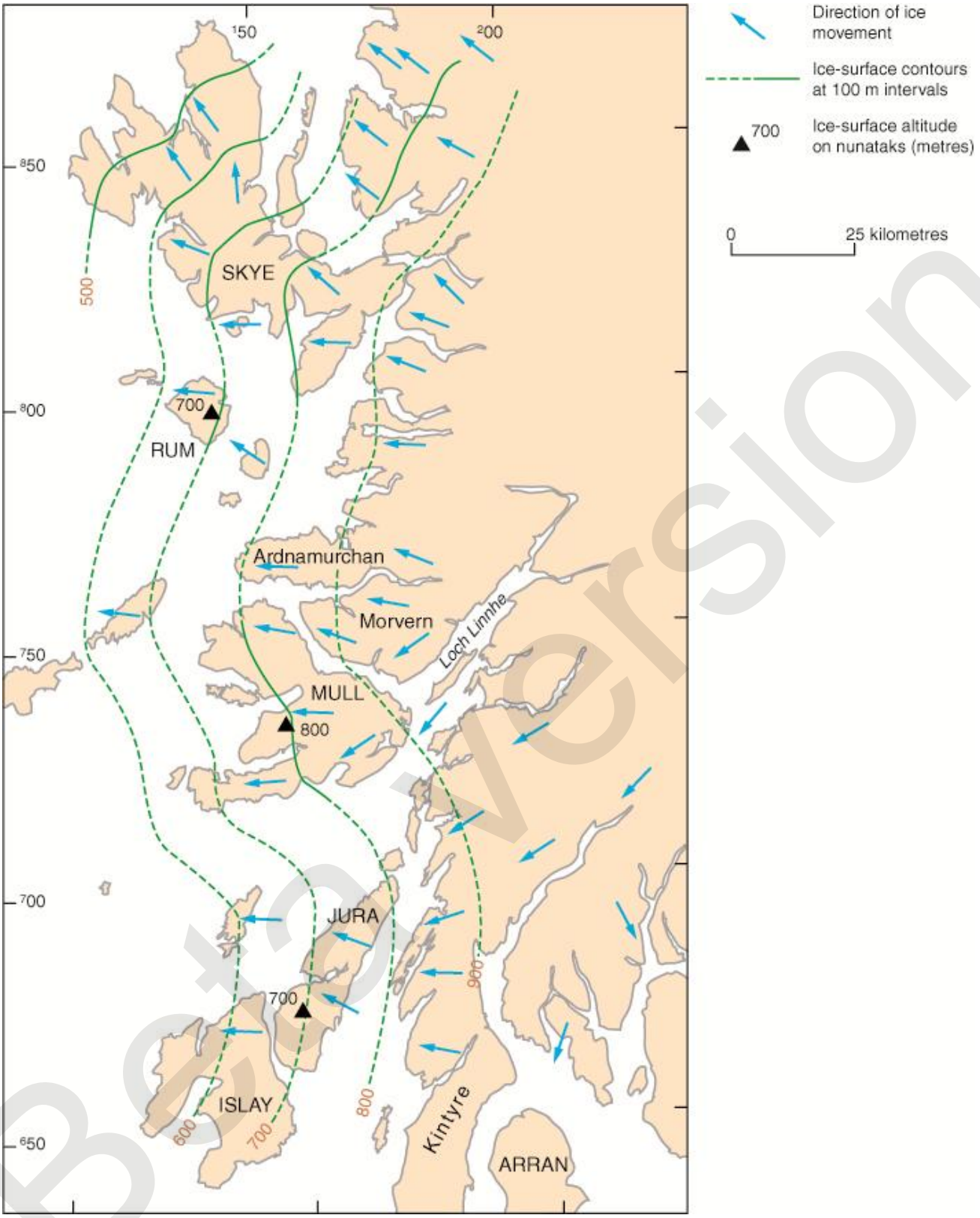


Figure 13-71: Reconstruction of the ice sheet in the Inner Hebrides and the Scottish Mainland during the maximum of the Late Devensian Glaciation, based on an assumed maximum ice surface altitude of *ca.* 800 m on Ben More, Mull (after Ballantyne 1999).

Skye was an important centre of ice-sheet glaciation, and the Cuillin represents one of the most outstanding areas in Britain for the study of glacial geomorphology (see figures throughout this chapter). The distribution of glacial striae, ice-moulded bedrock and erratics indicates that the Cuillin and Red Hills

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were not overridden by ice sourced from the Scottish Mainland during the Main Late Devensian. Instead, independent ice caps developed over central Skye, generating predominantly radial ice flow and deflecting mainland-derived ice into adjacent marine troughs (Figure 13-72; Figure 13-73). The presence of Scottish Mainland erratics across a wide altitudinal range on Raasay and Scalpay to the north, and on Soay to the south, together with their absence from the upland areas of the Cuillin and Red Hills, defines the area unaffected by mainland ice (Figure 13-74; Figure 13-75; Figure 13-76) (Harker 1901, but see also Ballantyne 1990).

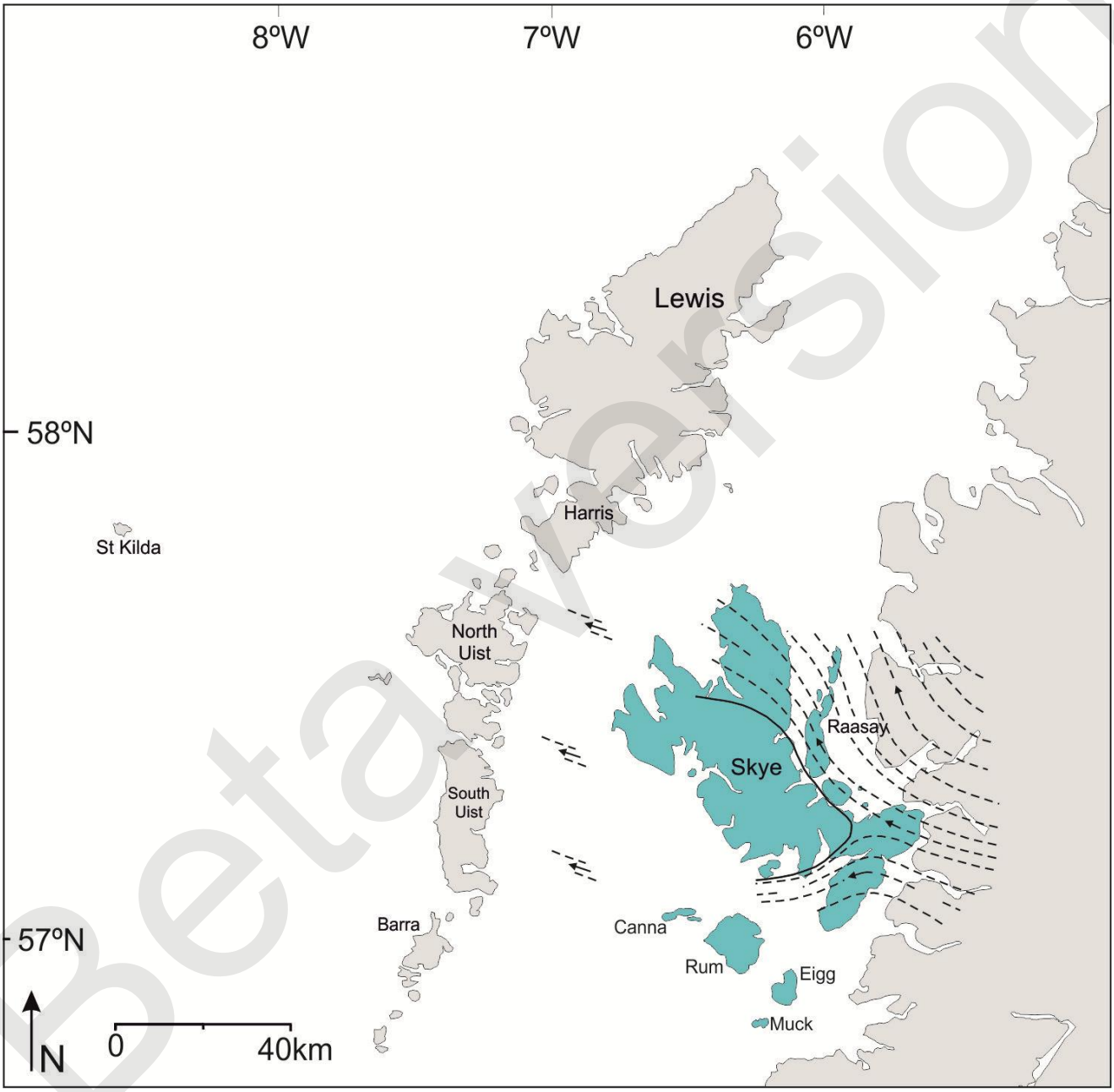


Figure 13-72: Harker's (1901) sketch map illustrating his interpretation of how Scottish Mainland-derived ('foreign') ice flow was deflected by the Skye-centric ('native') ice field, hence Scottish Mainland erratics are absent inside the dashed line.

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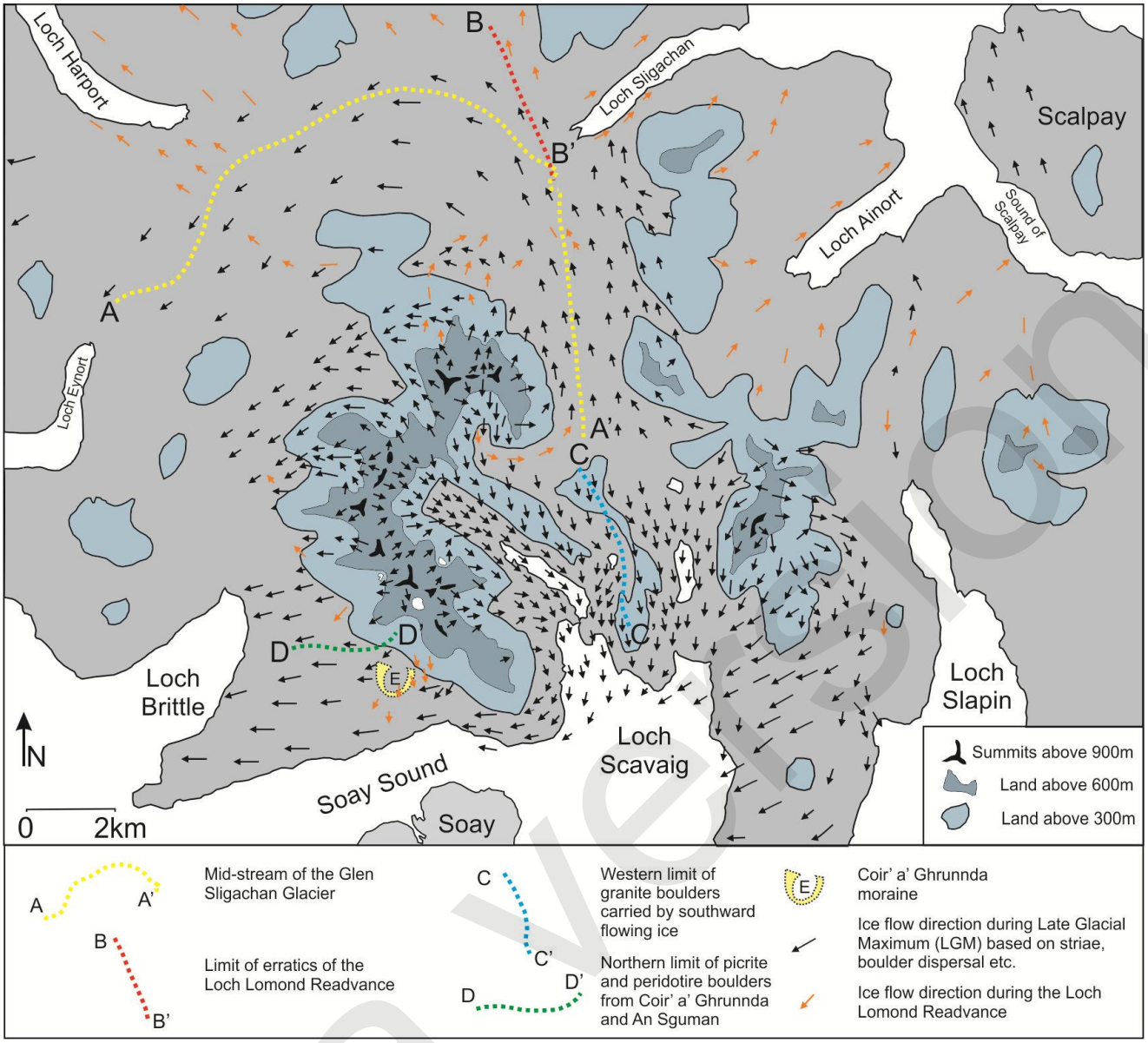


Figure 13-73: Harker's (1901) sketch map illustrating the central part of Skye and its glacially related features.

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Figure 13-74: Erratics of Lewisian gneiss, atop Sgiath-bheinn an Uird, Sleat; deposited from the main east-to-west flowing 'Mainland' glacier system. Pole *ca.* 1 m long.



Figure 13-75: Erratics of Lewisian gneiss, atop Sgiath-bheinn an Uird, Sleat; deposited from the main east-to-west flowing 'Mainland' glacier system. Pole *ca.* 1 m long.

Revision

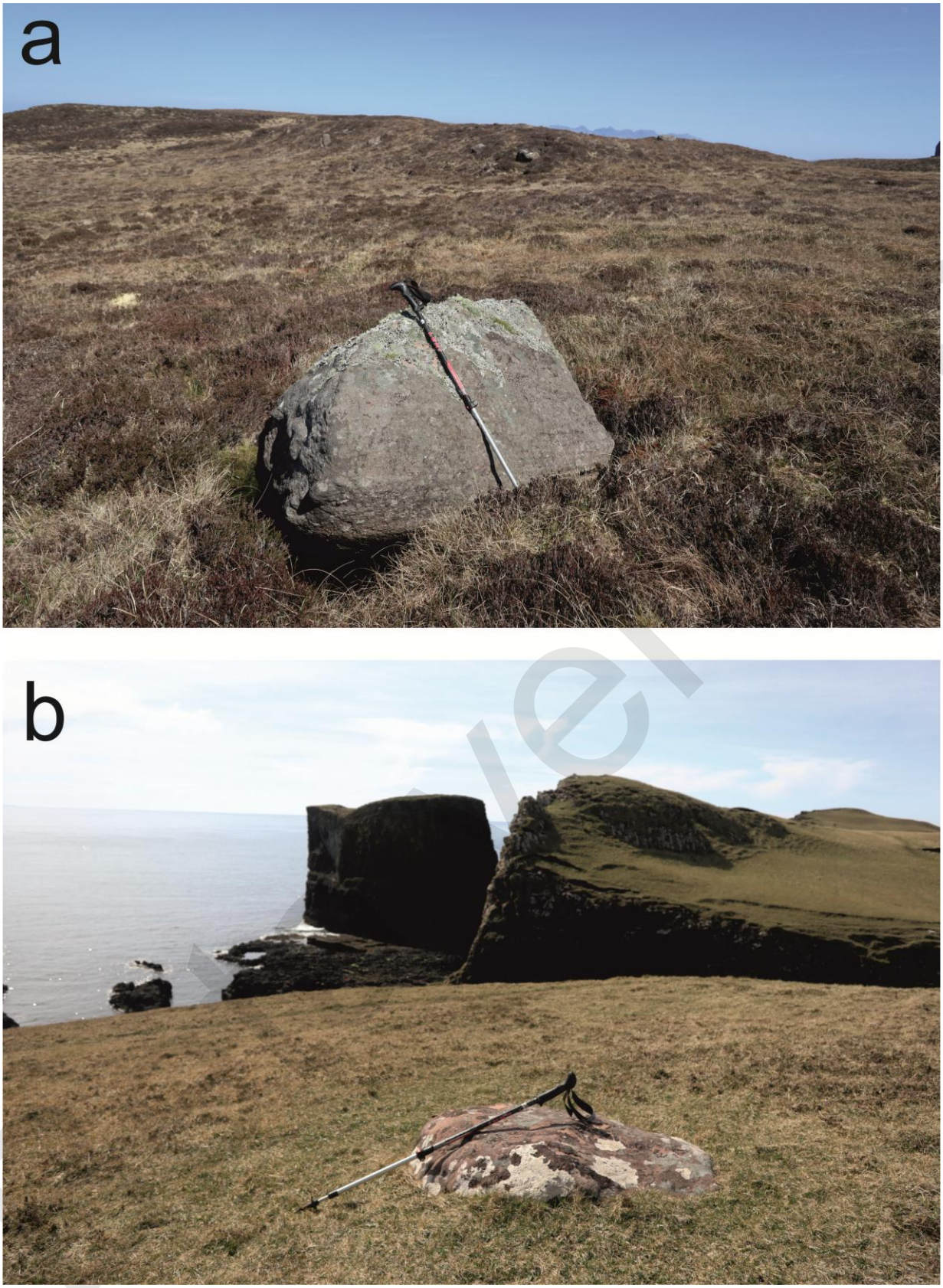


Figure 13-76: Glacial erratics of pale orange-red Torridonian sandstone on (a) Canna, and (b) Sanday, deposited from the main east-to-west flowing 'Mainland' glacier system. Pole *ca.* 1 m long.

The former height of the Main Late Devensian ice cap has been established by the mapping of glacial trimlines around mountains that stood above the ice as nunataks in central and northern Skye (Ballantyne 1990) (Figure 13-77; Figure 13-78). The term is used variably in the literature, including periglacial weathering limit and ice-surface limit; key features used to identify trimlines include the contrast in weathering and soil chemistry (Ballantyne 1997). High-level, Main Late Devensian trimlines have been recognised on the higher peaks of the Cuillin and on Blà Bheinn, on certain of the high peaks in the Red Hills, along the Trotternish Escarpment, and on Healabhal Bheag in Duirinish, west Skye (Dahl *et al.* 1996).

Trimlines across the Cuillin massif mark a clear boundary between ice-moulded lower slopes and extensively frost-shattered, blockfield-mantled upper slopes. These periglacial trimlines (*ca.* 750–870 m OD) have been used to reconstruct the maximum elevation of Late Devensian ice and to delimit Loch Lomond (Younger Dryas) and younger ice extents on Skye (see below) (Dahl *et al.* 1996; Ballantyne 1997). The Blà Bheinn outlier preserves a trimline, determined from advanced weathering above a lower glacially scoured zone.

The Trotternish escarpment of north Skye exhibits a pronounced lower weathering limit where basaltic summits preserve deep weathering (gibbsite/advanced weathering) and lower slopes show glacial polishing and transported material. Ballantyne (1994) used X-ray soil data and geomorphological mapping to argue these surfaces mark former nunatak/periglacial limits and to constrain ice elevations in northern Skye. On Trotternish, the Main Late Devensian trimline descends from 580-610 m OD in the south, to 440-470 m OD in the north, within a distance of *ca.* 24 km.

Glamaig and adjacent Red-Hills of central Skye display a high-level periglacial trimline, *ca.* 760 m on Glamaig. The contrast in rock character above/below this trimline has been used in reconstructing local Loch Lomond Stadial glacier extents and in broader compilations of Scottish trimline altitudes (Dahl *et al.* 1996; Ballantyne 1997).

Duirinish in west Skye (MacLeod's Tables), preserves trimline evidence where blockfield and weathered plateau surfaces survive above glacially eroded lower slopes. The periglacial trimline recognised by Ballantyne (1997) is based on high-level weathering limits and is used to determine the extent of ice cover and nunatak survival.

Rum preserves classic trimline evidence used by Ballantyne (1980) and Ballantyne & McCarroll (1997) to define the maximum altitude of the Late Devensian ice sheet on the island. The Rum Cuillin shows clear blockfield/soil development above contrasting glacially scoured corrie floors and valleys; these relations underpin reconstructions of Loch Lomond-stadial glaciers on the island.

On Mull, mapped trimlines separate frost-weathered summits and blockfields from extensive ice-moulded lower ground. Glacier reconstructions for Mull by Ballantyne (2002) use trimlines as key markers for reconstructing a Loch Lomond Stadial alpine-type icefield and for estimating ice thickness.

Several other local trimlines have been mapped and discussed in site studies and regional syntheses, for example, trimlines on Harris and North Lewis in the wider Outer Hebrides context, and minor trimlines on Eigg and Canna (Rae 2004; Ballantyne & Small 2018).

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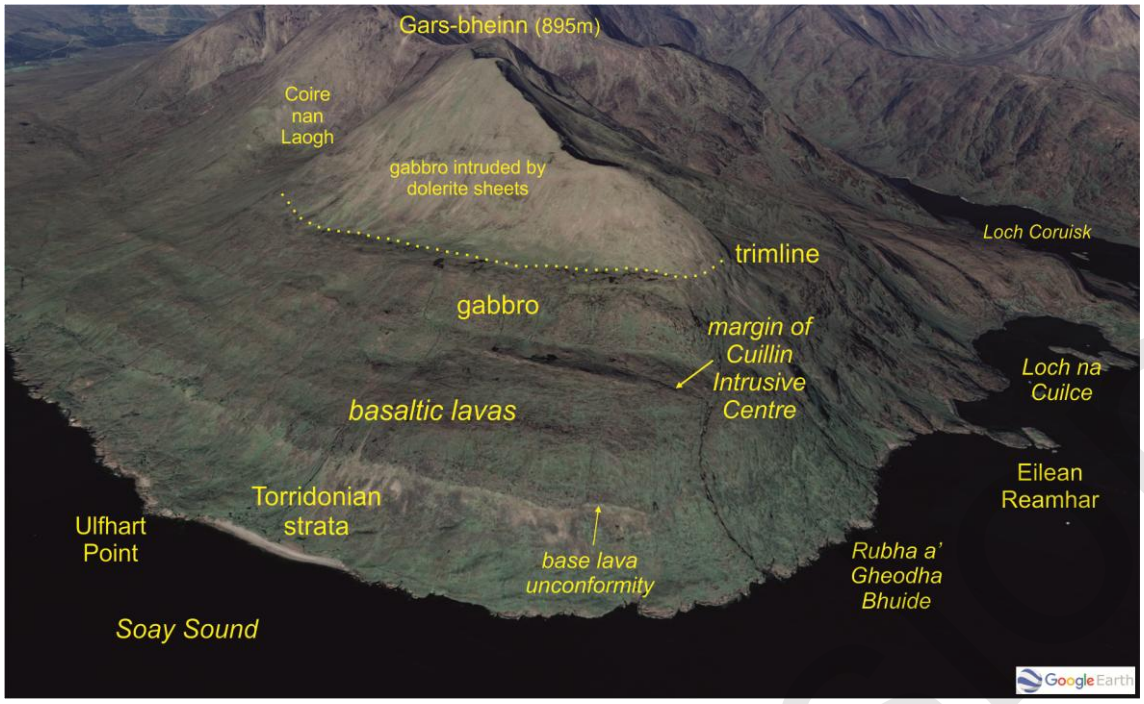


Figure 13-77: Oblique Google Earth© Image illustrating a trimline in the southern Cuillin, Skye, on the southern slopes of Gars-bheinn. The contrasting lithologies above (microgabbro and dolerite) and below (gabbro, basalt and sandstone) may, in part, be responsible for the contrasting weathering and erosion characteristics, with abundant loose blocks and scree above the trimline. View towards the NW.



Figure 13-78: Field view of Gars-bheinn, southern Cuillin, with abundant ice-weathered/shattered material on the higher ground. View towards the north from Soay.

Frost-weathered bedrock (regolith) is common above the trimlines in the summit regions of the Cuillin and the Red Hills (Figure 13-79; Figure 13-80). In these areas, relict solifluction sheets and lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age are also preserved, for example on Druim na Ruaige, on the west side of Beinn Dearg in the Western Red Hills (Figure 13-81).

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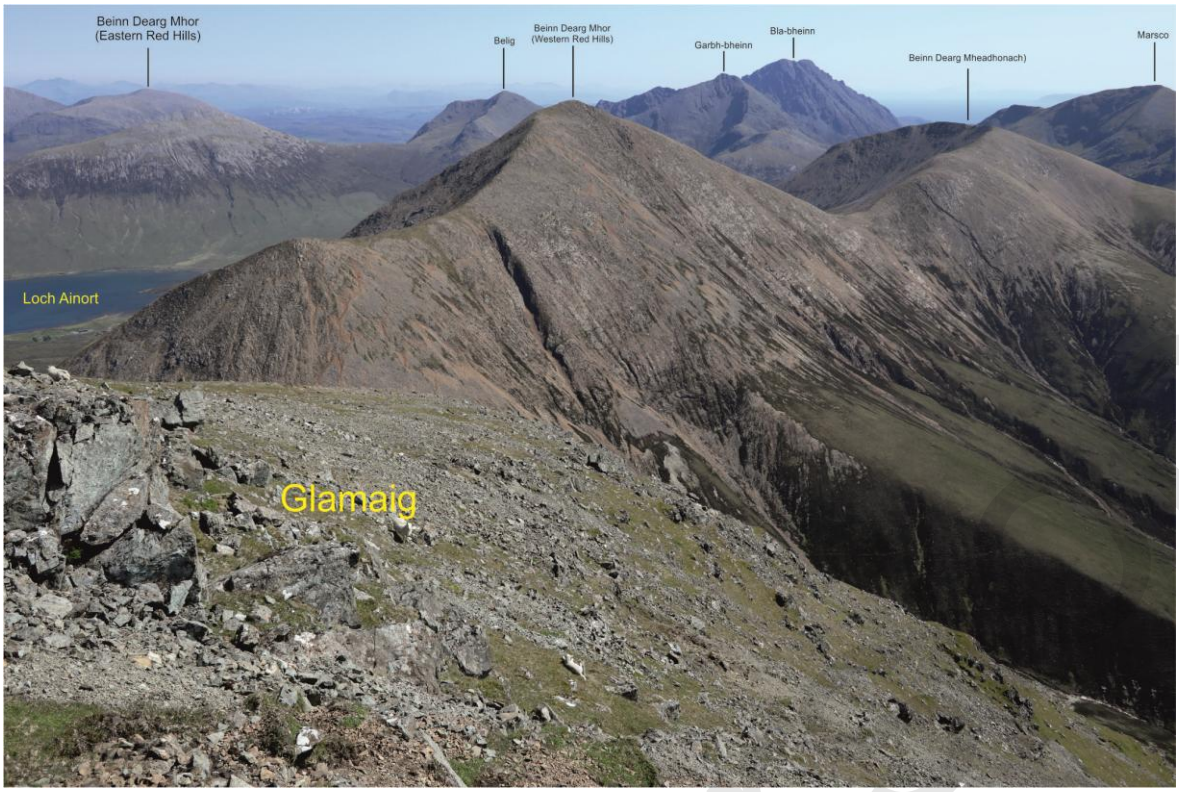


Figure 13-79: Frost-weathered/shattered bedrock on the summit of Glamaig (foreground) and on the summit areas of the granite Red Hills, Beinn Dearg Mhòr and Beinn Dearg Mheadhonach, and the gabbro- and dolerite-dominated Blà Bheinn.



Figure 13-80: Frost-weathered bedrock, mainly Paleocene silicic volcanic rocks in Fionn Choire, northern Cuillin, Skye. View towards the east, with Glamaig in the distance.

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Figure 13-81: Relict solifluction sheets and lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age on Druim na Ruaige on the west side of Beinn Dearg Mheadhonach, Skye.

Talus slopes of similar age are preserved on Strathaird, south-central Skye, on Ben Méabost and An Càrnach (Figure 13-82; Figure 13-83**)**. Multiple examples are recognised in north and west Skye (Figure 13-84).

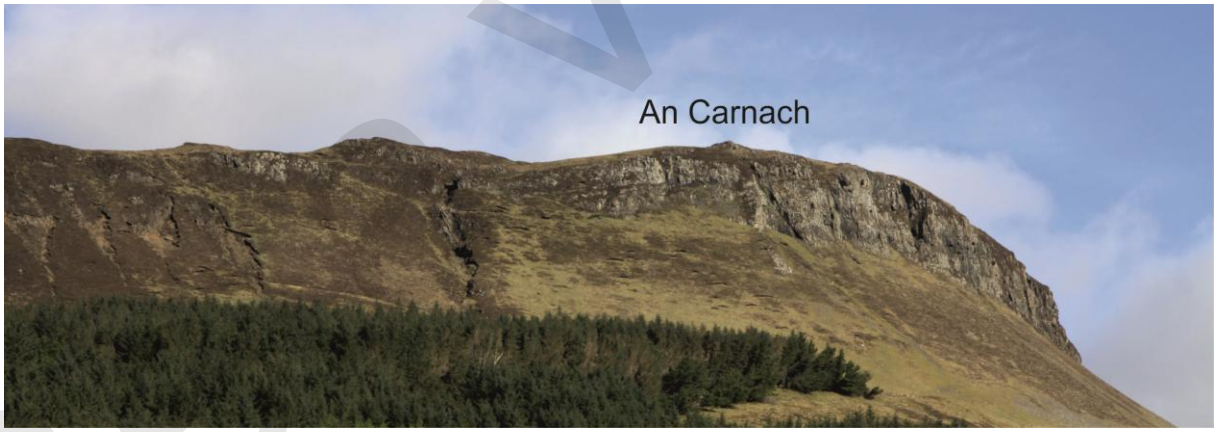


Figure 13-82: Relict talus lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age, An Carnach, Strathaird, Skye.

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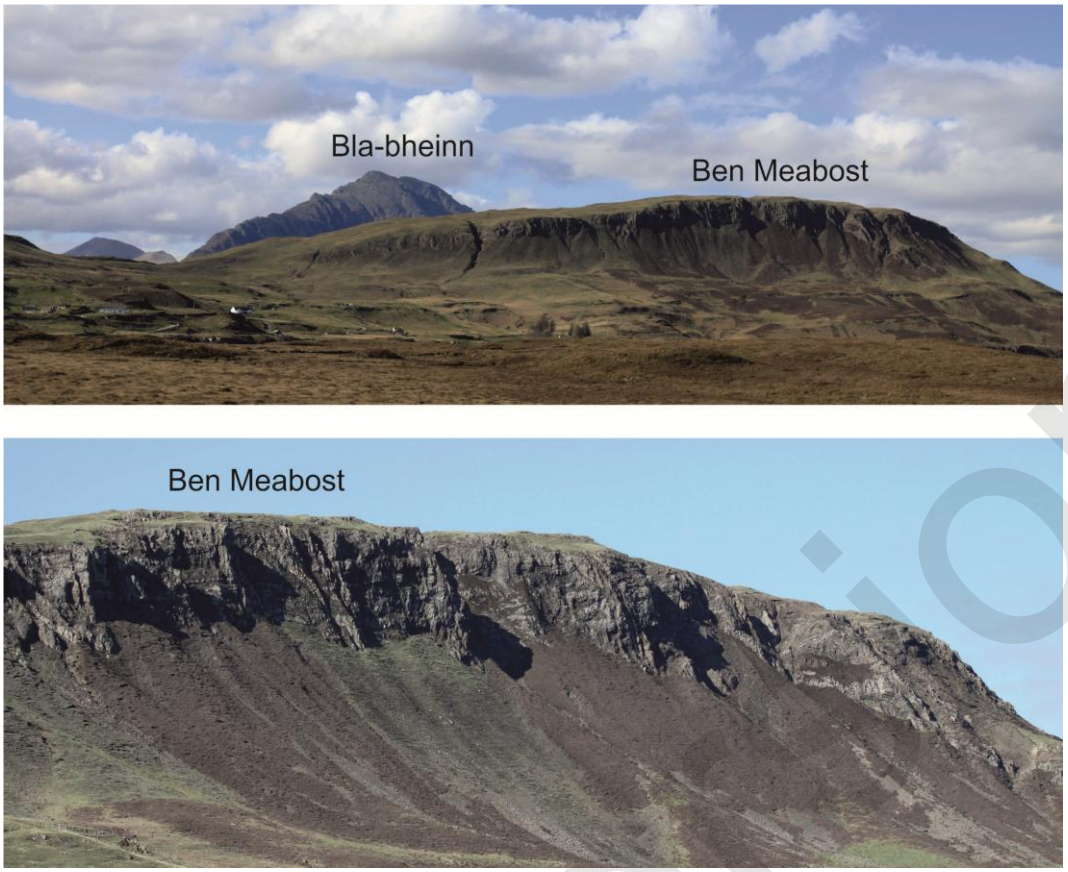


Figure 13-83: Relict talus lobes of Late Devensian (Main Late Devensian and/or Loch Lomond Stadial) age, Ben Meabost, Strathaird, Skye.



Figure 13-84: Recent talus overlying relect talus, Mointeach nan Tarbh, Duirinish, Skye.

These features are identified by their relatively complete vegetation cover when compared with features forming at the present day. Some of the extensive landslips on Trotternish, Skye, also predate the

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Holocene (see below). In the later stages of the Main Late Devensian Glaciation, as the pressure of the Scottish Mainland ice decreased, the ice cap over the Cuillin and the Red Hills was able to spread outwards. Supporting evidence comes from the Allt Beinn Deirge area, SE of Beinn na Caillich, where unconsolidated deposits outside the limit of the later, Loch Lomond Stadial glaciation have been deformed by ice moving in an easterly direction (Le Coeur & Kuzucuoglu 1992) (Figure 13-85).

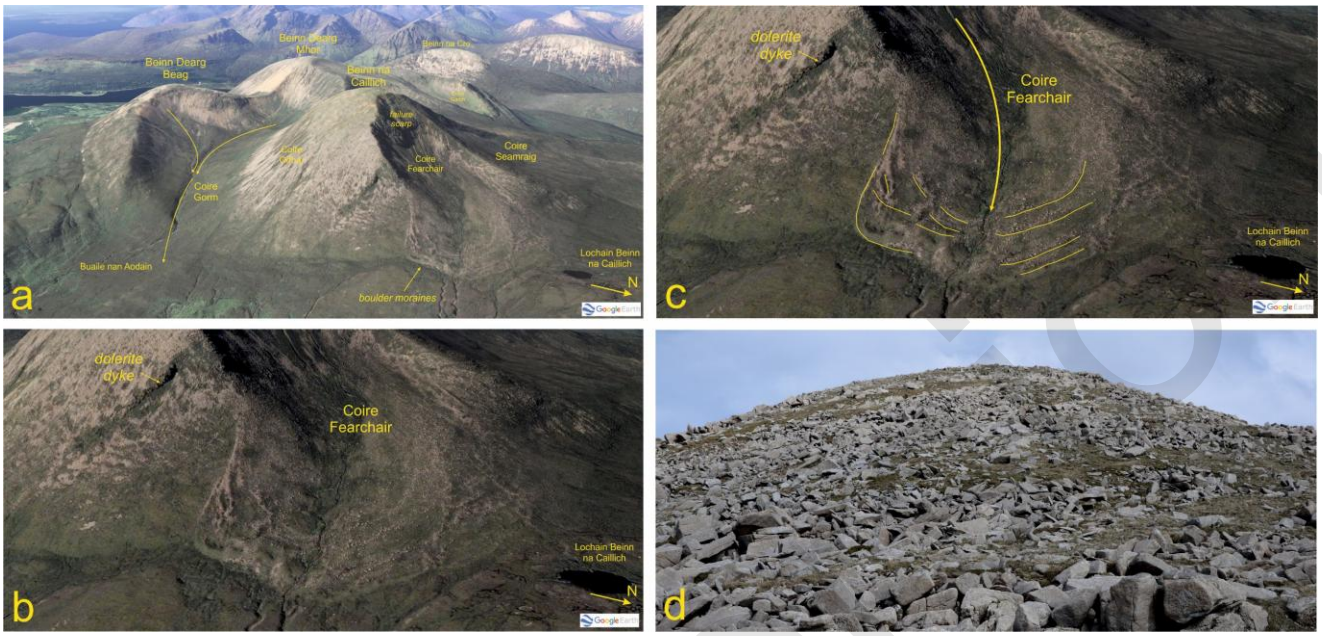


Figure 13-85: (a) Oblique Google Earth© schematic image interpretation of the Coire Gorm (Eastern Red Hills, Skye) (Loch Lomond Re-advance) glacier(s), arrowed; (b) Coire Fearchair boulder moraines (uninterpreted); (c) Coire Fearchair boulder moraines (interpreted); and, (d) detail of boulder moraine.

The mountains of south-central Rum may have supported an independent ice dome during the Main Late Devensian Glaciation. However, the distribution of striae and erratics on the lower ground, and on all the adjacent islands, show that the other islands of the Small Isles were over-ridden by Scottish Mainland ice, which was diverted around the mountains of Rum. On Eigg, striae indicate westward movement of ice, with possible diversion around the ridge of An Sgùrr. There are no convincing striae on Muck, but on Canna and Sanday striae indicate ice flow towards the NW and west, respectively.

Amongst the distinctive erratics found in the Small Isles are: Moine gneiss on Rum; gneiss, limestone of both Cambro-Ordovician and Jurassic age, and Torridon Group sandstone on Canna and Sanday; and, gabbro, basalt, gneiss, mica-schist, quartzite, Torridonian and Mesozoic sandstone on Oigh-sgeir (suggestive of derivation from the Scottish Mainland, Rum and the surrounding seabed); and, Moine gneiss on Eigg and Muck.

Scottish Mainland erratics have not, however, been found on the high ground in northern Eigg. Till deposits attributable to the Main Late Devensian Glaciation are common on Rum and small patches of till occur on the other islands, but glaciofluvial deposits are everywhere rare. There are two prominent NE-trending morainic ridges in NE Eigg. The eastern ridge is most likely part of a large crag-and-tail structure produced by ice flowing around the north end of Eigg, whereas the western ridge is a lateral moraine formed as the same ice mass decayed. Good examples of kettleholes occur in Cleadale, on Eigg (Figure 13-86).

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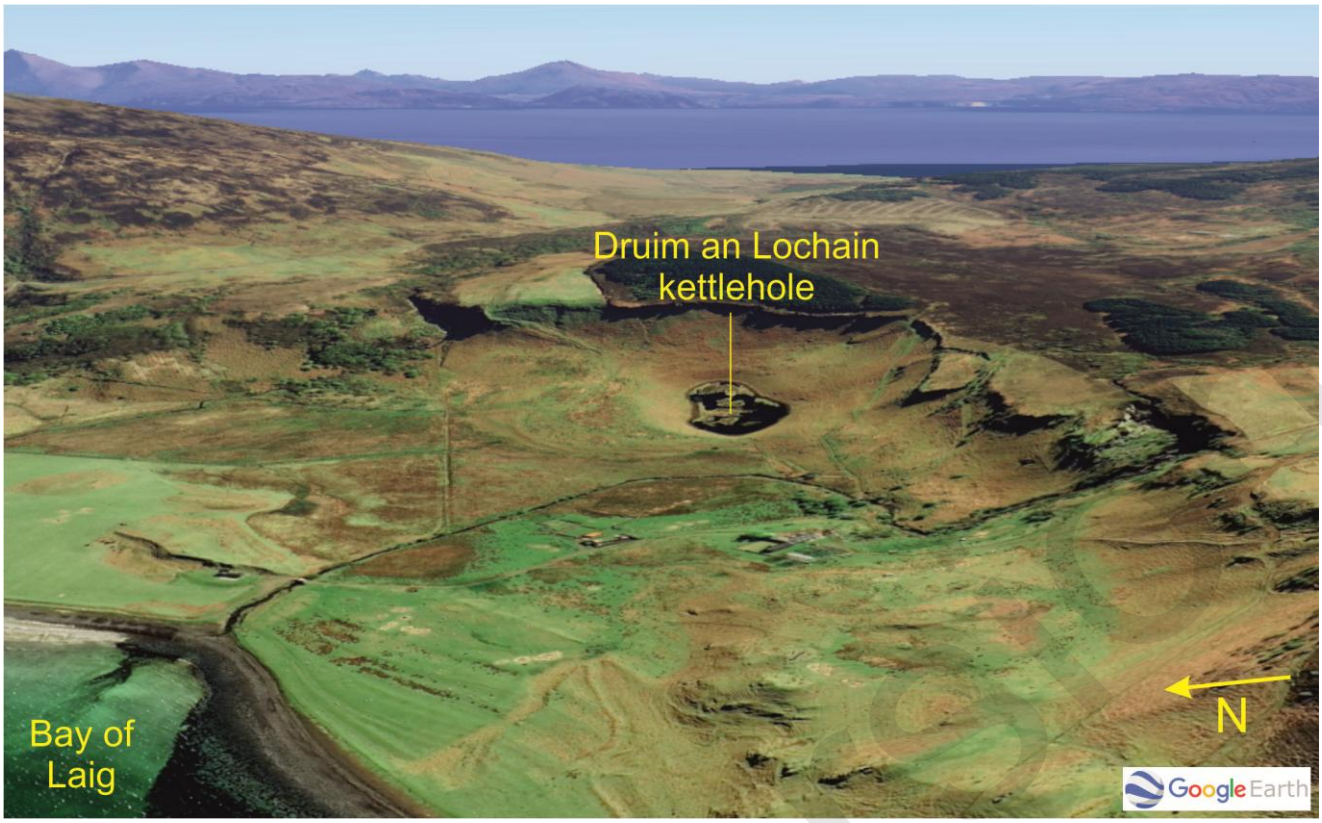


Figure 13-86: Oblique Google Earth© Image of Druim an Lochain kettlehole, south of Laig Bay, Eigg.

The glaciation of Mull during the Loch Lomond Stadial (see below) removed much of the evidence for earlier glaciations from the central parts of the island. A local ice dome was established over the hills of central Mull during the Main Late Devensian Glaciation, diverting the Scottish Mainland ice down Glen Forsa and SW along Glen More and Loch na Keal (Bailey *et al.* 1924) (Figure 13-87; Figure 13-88; Figure 13-89). Ben More and other high peaks most likely formed nunataks (Ballantyne 1999).

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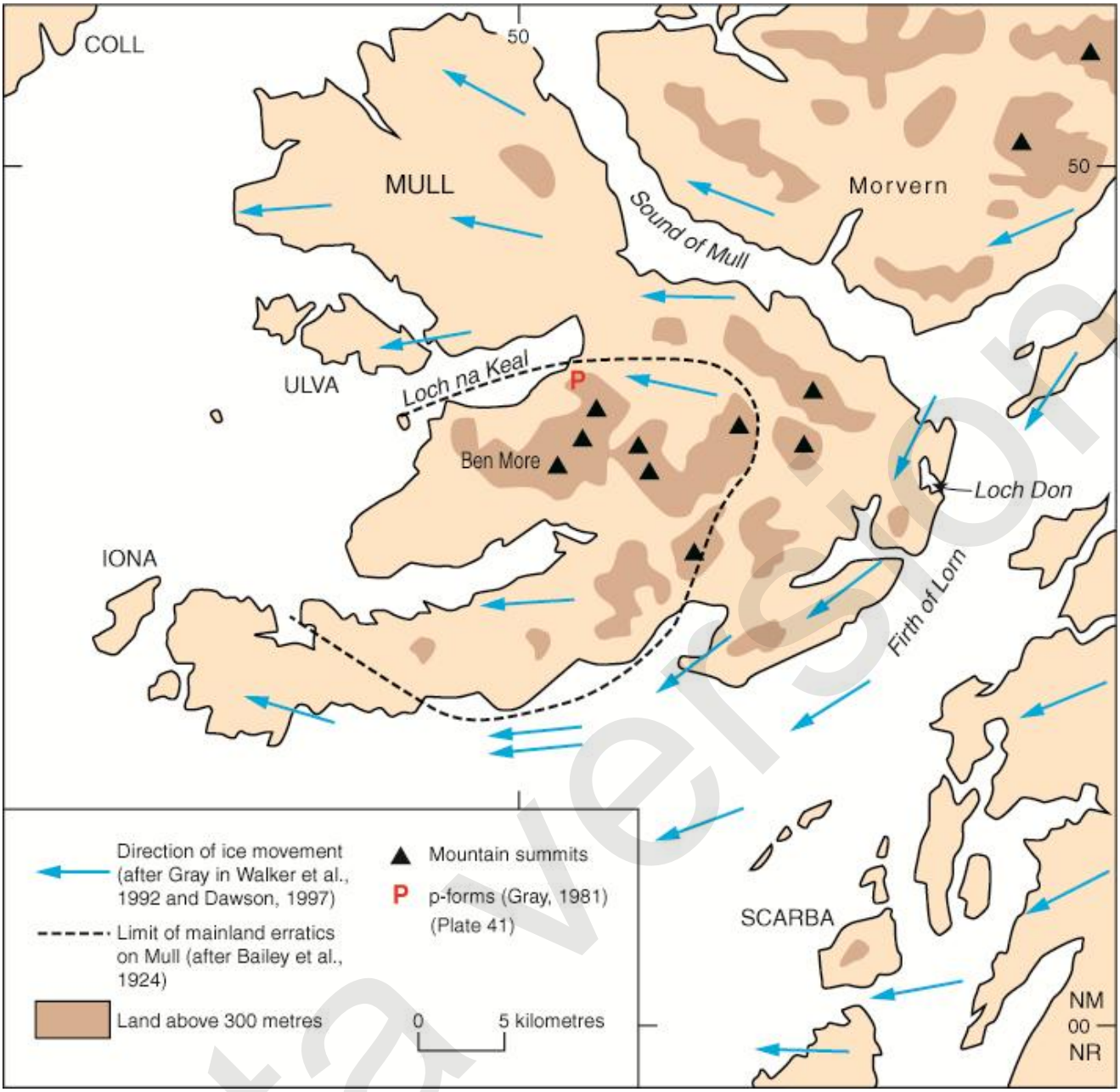


Figure 13-87: Direction of ice movement around Mull during the Main Late Devensian Glaciation. A local ice dome over the mountains of southern Mull deflected the ice that flowed from the Scottish Mainland and hence mainland erratics are absent inside the dashed line (after Ballantyne 1999).

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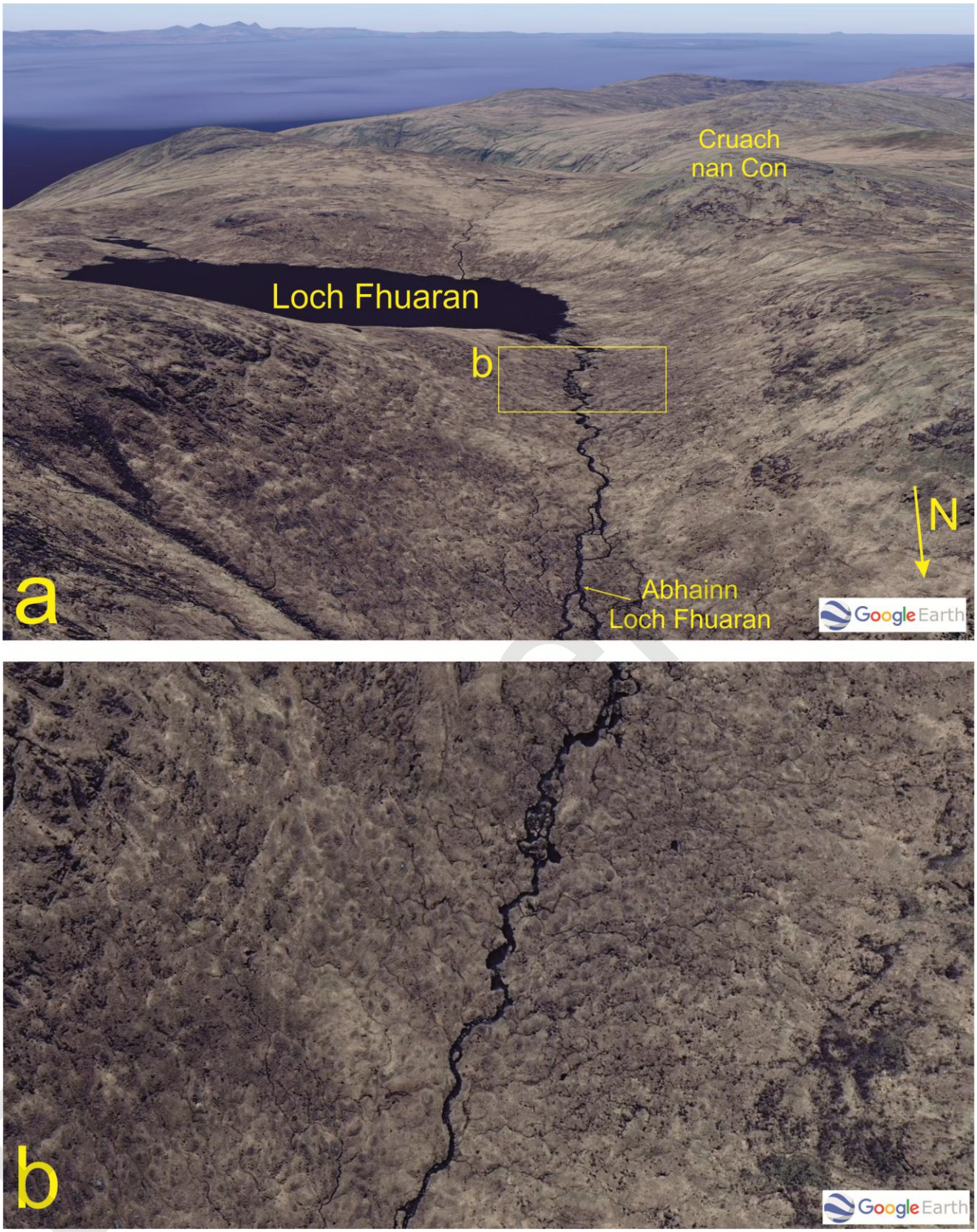


Figure 13-88: Oblique Google Earth© image of sub-glacially formed moraine deposits north of Loch Fhuaran, SW Mull.



Figure 13-89: Sub-glacially formed moraine deposits, Glen More, SE Mull.

On the south side of Loch na Keal, for some distance on either side of the outlet of the Scarisdale River, bare basalt slabs on the shoreface have been moulded into a striking assemblage of smoothed, fluted, channel-like forms a metre of so in depth and a few metres in length (Figure 13-90). These are termed 'p-forms' (plastically moulded forms) and are excellent examples of structures that originated by a combination of erosion by glacial meltwaters and overlying ice (Gray 1981; Walker *et al*. 1992).



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Figure 13-90: 'P-form channel' scoured in basalt by glacial meltwater, south shore of Loch na Keal, Scarisdale, central Mull. Pole *ca*. 1 m long.

Bid version

At the northern end of Loch Don, deltaic sands and gravels were deposited where south- and SE-flowing meltwater streams entered the sea, to form the lower levels of the 'Loch Don Sand-Moraine' (Bailey *et al*. 1924; Benn & Evans 1993; see below).

The Ardnamurchan peninsula was completely over-ridden by Scottish Mainland ice during the Main Late Devensian Glaciation but apparently escaped renewed glaciation during the Loch Lomond Stadial. Evidence for ice movement from the SE is provided by numerous striae and by the distribution and character of glacial erratics, including many derived from the Strontian Granite Pluton which occur, for example, on Ben Hiant. Much ice sculpting of the bare rocks has occurred, and the hills formed by the Paleocene gabbroic ring-intrusions (Chapter 9) provide numerous examples of roches moutonnées (Figure 13-91; Figure 13-92; Figure 13-93).



Figure 13-91: The glacially sculpted gabbro of Meall Sanna, Ardnamurchan, with, beyond, the An Sgùrr ridge of Eigg.

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Figure 13-92: Homogeneous, ice-moulded quartz gabbro, Beinn na Seilg. View NW towards Loch Grigadale, Ardnamurchan.



Figure 13-93: The glacially sculpted gabbro and dolerite intrusions of Beinn na Urchrach and (beyond) Ben Hiant, Ardnamurchan. View towards the east from Kilchoan.

The Scottish Mainland ice sheet centred over the Highlands extended across Arran for most of the Main Late Devensian Glaciation. However, by *ca*. 13,000 years BP, the southern limit of the ice sheet on Arran lay along a line from Imachar to Corrie, with a detached remnant over the high ground to the south. By 12,400 years BP, the island was free of Scottish Mainland ice, although a local ice cap may have persisted on the northern hills. The south of Arran escaped glaciation during the Loch Lomond Stadial and, consequently, deposits of an earlier glacial episode are widely preserved in that area. Reddish till, coloured by debris from the New Red Sandstone, is commonly exposed in river and stream sections, and in the Sliddery Water and Kilmory Water a clay bed near the base of the till contains a perfectly preserved shelly fauna (Tyrrell 1928). Enigmatically, this fauna exhibits both Arctic and temperate characteristics (Sutherland 1981).

A large variety of features associated with the decay of the Main Late Devensian ice are preserved in the low ground of SW Arran (Gemmell 1972), including a succession of kame terraces NE of Shiskine and drumlins near Blackwaterfoot. SW-draining meltwater channels occur on the western slopes of Beinn Tarsuinn (near Blackwaterfoot) and south of Glen Iorsa. Moraines in Benlister Glen are most likely of comparable age, recording the retreat of the Main Late Devensian ice. At the head of Glen Cloy, a raised shoreline estimated to date from *ca*. 12,000 years BP cuts outwash from moraines in the glen. Deposits of gravelly till derived from readily weathered granite are restricted to the northern hills and the mouths of the valleys draining the granites. These deposits, which are up to 15 m thick, most likely formed as the local ice decayed, after Arran became isolated from the Scottish Mainland ice.

Ailsa Craig, 20 km south of Arran, lay in the path of a south-flowing stream of Scottish Mainland ice that helped mould it into its present steep-sided dome shape (Figure 13-94; Figure 13-95). The distinctive blue-grey Ailsa Craig microgranite (Chapter 9) is widely distributed as glacial erratics and ice-rafted stones on coasts bordering the southern Firth of Clyde, in the north of County Antrim and on both sides of the Irish Sea as far south as Cork and Pembroke (Harrison *et al*. 1987). The distinctive pebbles and cobbles are also found on beaches in western Arran, where they may have been carried by drifting icebergs during the decay of the Firth of Clyde ice sheet.

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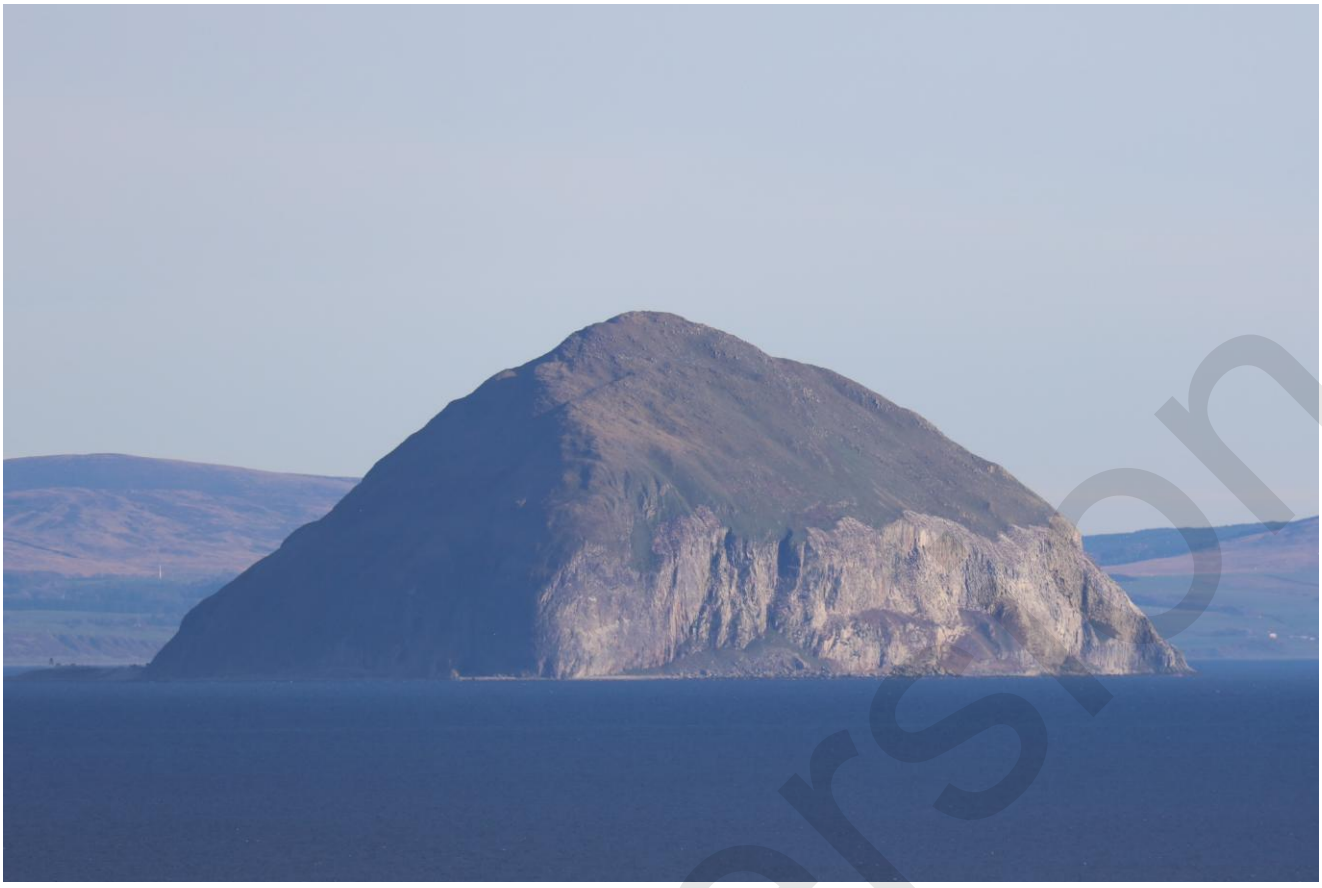


Figure 13-94: The ice-sculpted island of Ailsa Craig in the Firth of Clyde, 20 km south of Arran. View towards the south from Sliddery, south Arran.



Figure 13-95: The ice-sculpted island of Ailsa Craig in the Firth of Clyde, 20 km south of Arran. View towards north.

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13.7 Windermere Interstadial

Deposits relating to the warm Windermere (Late-glacial) Interstadial (13,000 to 11,000 years BP) (Figure 13-2) are of limited occurrence in the district. Sediments at the base of a succession sampled from Loch an t-Suidhe on the Ross of Mull, yield a ^{14}C age of 13,100 years BP, while clays with a molluscan fauna of interstadial affinities have been identified in a few localities, for example on the floor of Loch Arienas north of Loch Aline in Morvern. Sedimentary deposits from this period are also found on the south shore of Loch Spelve, Mull (Walker *et al.* 1985), and at Kinlochspelve, where shells have been dated at 11,330 ± 170 years BP. The latter deposits were subsequently disturbed by a subsequent glacial event. In general, these beds may correlate with the Late-glacial Clyde Beds of the Midland Valley of Scotland (e.g. Peacock 1981).

13.8 Loch Lomond Stadial

During the Loch Lomond Stadial (12,900 to 11,700 years BP; Figure 13-2), small ice fields and glaciers re-established in the mountainous areas of the district, leading to renewed valley and corrie glaciation, and to the modification or erosion of older glacial deposits; a distinctive suite of deposits is associated with this glaciation.

On Skye, glacial activity was centred over the Cuillin and the Western Red Hills (Figure 13-96). In addition, there were two small glaciers in NE-facing valleys on the Trotternish escarpment and glaciers in Kylerhea Glen and Glen Arroch in eastern Skye. The extent of the Cuillin ice field has been defined by the distribution and orientation of glacial striae, roches moutonnées and moraines, and by the lithologies and distribution patterns of glacial erratics (Figure 13-73; Figure 13-97; Figure 13-98; Figure 13-99; Figure 13-100; Figure 13-101). Outlet glaciers flowed northwards down Glen Sligachan into glens Drynoch and Varragill, and into Loch Sligachan; others were located along the north sides of the Western and Eastern Red Hills (Figure 13-102; Figure 13-103; Figure 13-104). To the south, a large glacier flowed into Loch Slapin and outlet glaciers formed in Srath na Crèitheach and from Loch Coruisk into Loch Scavaig (Figure 13-99). Nunataks protruding through the icefield included the main ridge of the Cuillin, together with Sgùrr na Stri and Blà Bheinn, and Marsco and Glamaig in the Western Red Hills (Figure 13-103; Figure 13-104).

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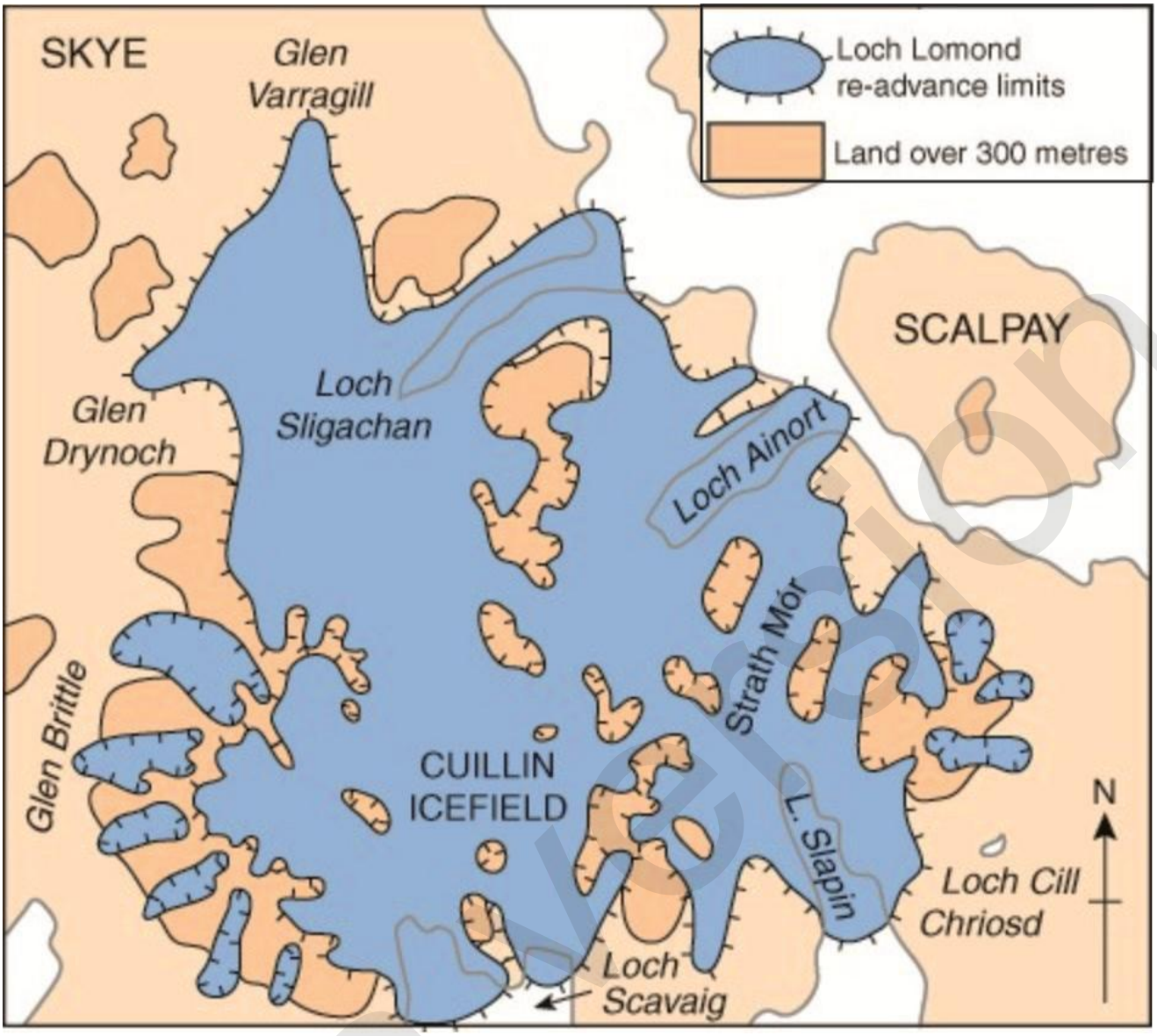


Figure 13-96: Limit of the local ice field on Skye during the Loch Lomond re-advance (after Benn *et al.* 1992).

Corries such as Coir' a' Ghrunnda, Coire Làgan, An Garbh-choire, Coir'-uisg and Lota Corrie, with their precipitous sides, rock falls and striated, ice-scoured rock in the corrie floors, provide some of the most spectacular glacial landforms in the district (Figure 13-97; Figure 13-98; Figure 13-99; Figure 13-100; Figure 13-101). Moraines and glacial trimlines generally help to define the extent and thickness of the corrie glaciers, although in the Red Hills this evidence is generally obscured by scree. Tills are common and typically have a sheet-like geometry within topographical depressions, although more-linear deposits are also present in the form of moraine ridges, as in the area around Sligachan. Excellent examples of moraines formed at glacier margins occur at the mouth of Coir' a' Ghrunnda in the Cuillin and at Coire Fearchair in the Eastern Red Hills (Figure 13-46; Figure 13-85; Figure 13-102). Hummocky moraine is common, containing material supplied from both subglacial and supraglacial environments (Figure 13-32; Figure 13-33; Figure 13-103; Figure 13-104; Figure 13-105).

In Gleann Torra-mhichaig, east of Glamaig, chains of hummocks oblique to the valley floor are attributed to intermittent bulldozing by advancing ice during the 'overall decay' of the valley glacier. In Coire Choinnich at the head of Loch Ainort, a chaotic assemblage of hummocks, non-aligned ridges and fluvial terrace accumulations resulted from the *in situ* decay of less-active glacier ice.

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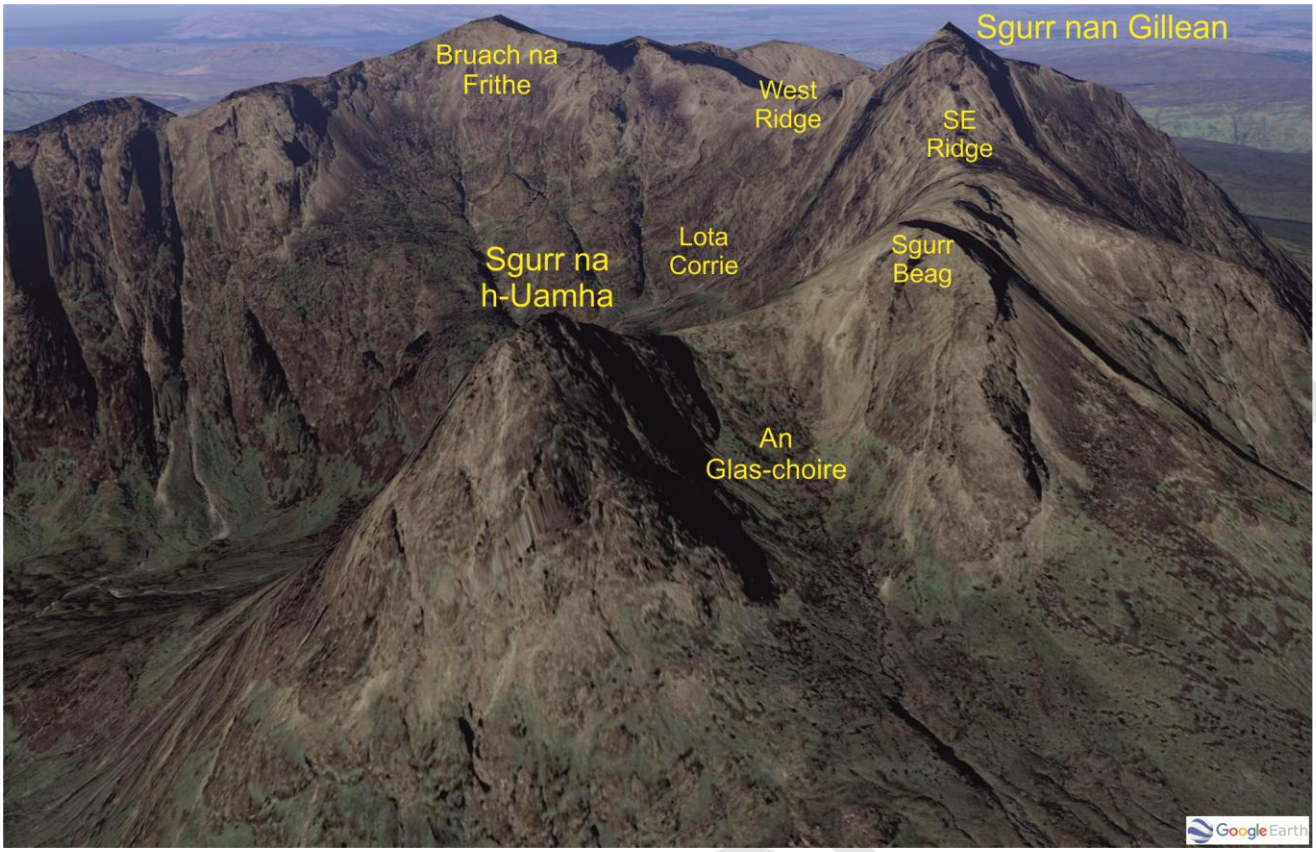


Figure 13-97: Oblique Google Earth© image illustrating arêtes (ridges) and arête pinnacles (pyramidal peaks, horns) in the northern Cuillin, Skye; the pinnacle of Sgùrr na h-Uamha (nearest), and the pinnacles of Sgùrr Beag and Sgùrr nan Gillean are connected by the arête known as the SE Ridge. Left of centre in the distance is Bruach na Frithe. View towards the west.

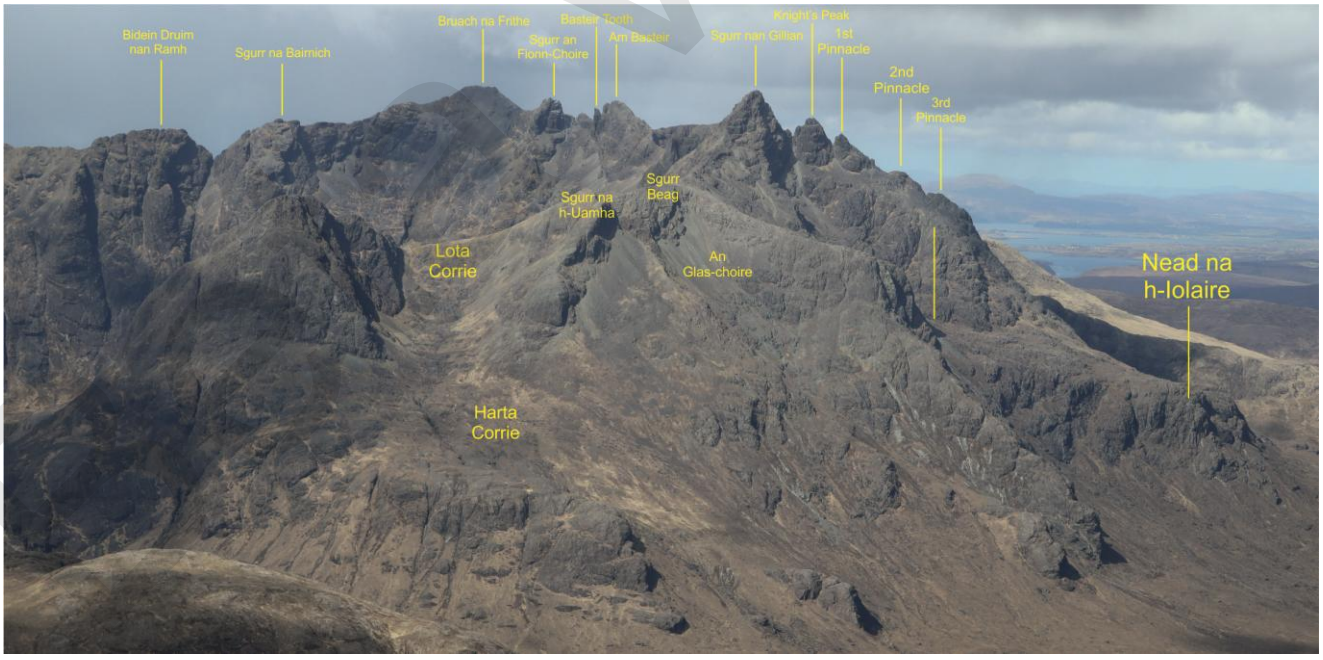


Figure 13-98: The northern part of the Cuillin Ridge, Skye, viewed towards the NW from Blà Bheinn, with named summits, ridges (arêtes) and corries.

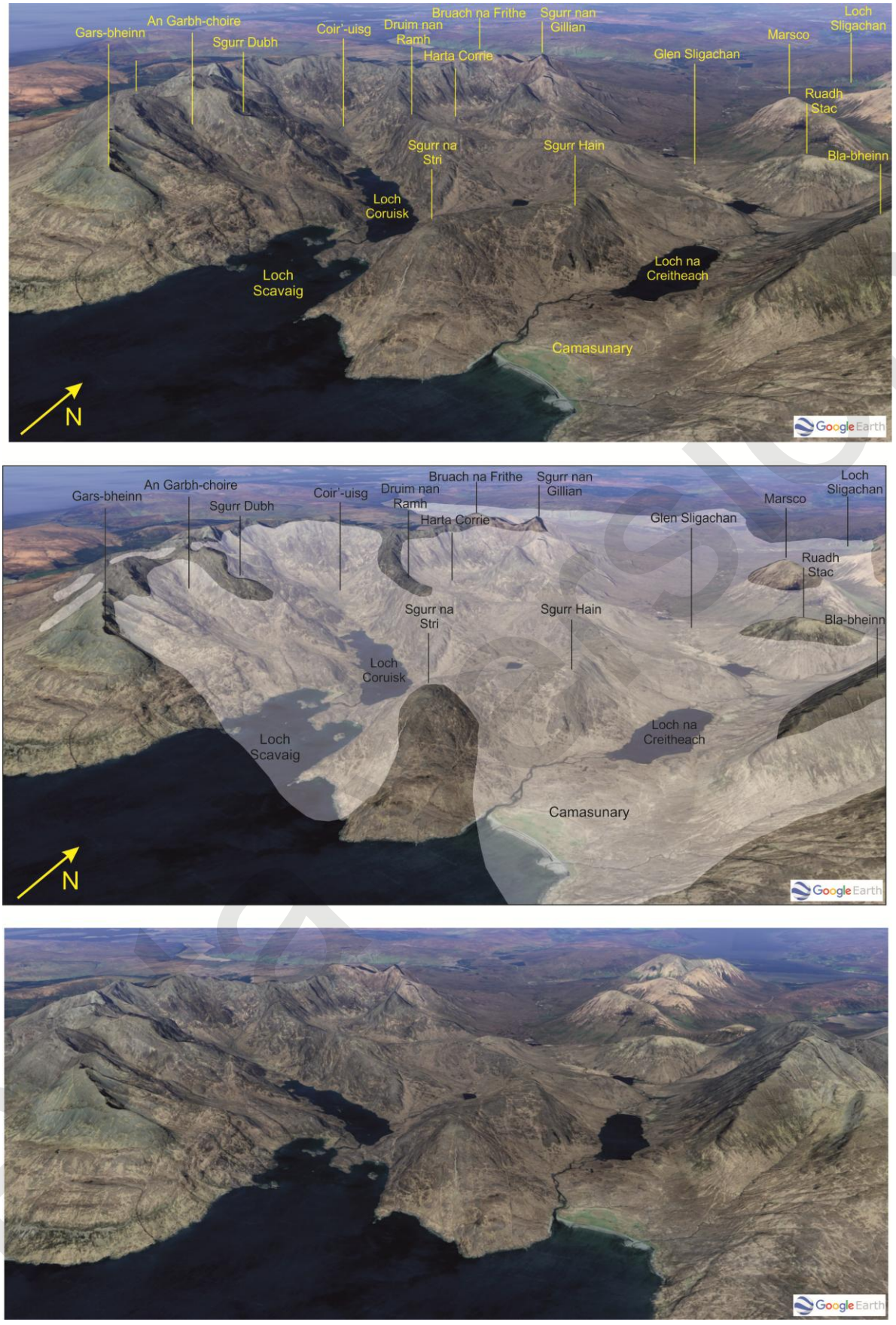


Figure 13-99: Oblique Google Earth© schematic image interpretation of the Cuillin (Loch Lomond Re-advance) glaciers.



Figure 13-100: The spine (ridge, arête) on the southern side of Blà Bheinn, east of the Cuillin, Skye. On the east (right-hand-) side of the arête, in the valley (corrie) of the Allt nan Leac, is a sub-glacially formed hummocky moraine.



Figure 13-101: Oblique Google Earth© image of sub-glacially formed moraine deposits, SE of Blà Bheinn, Skye.

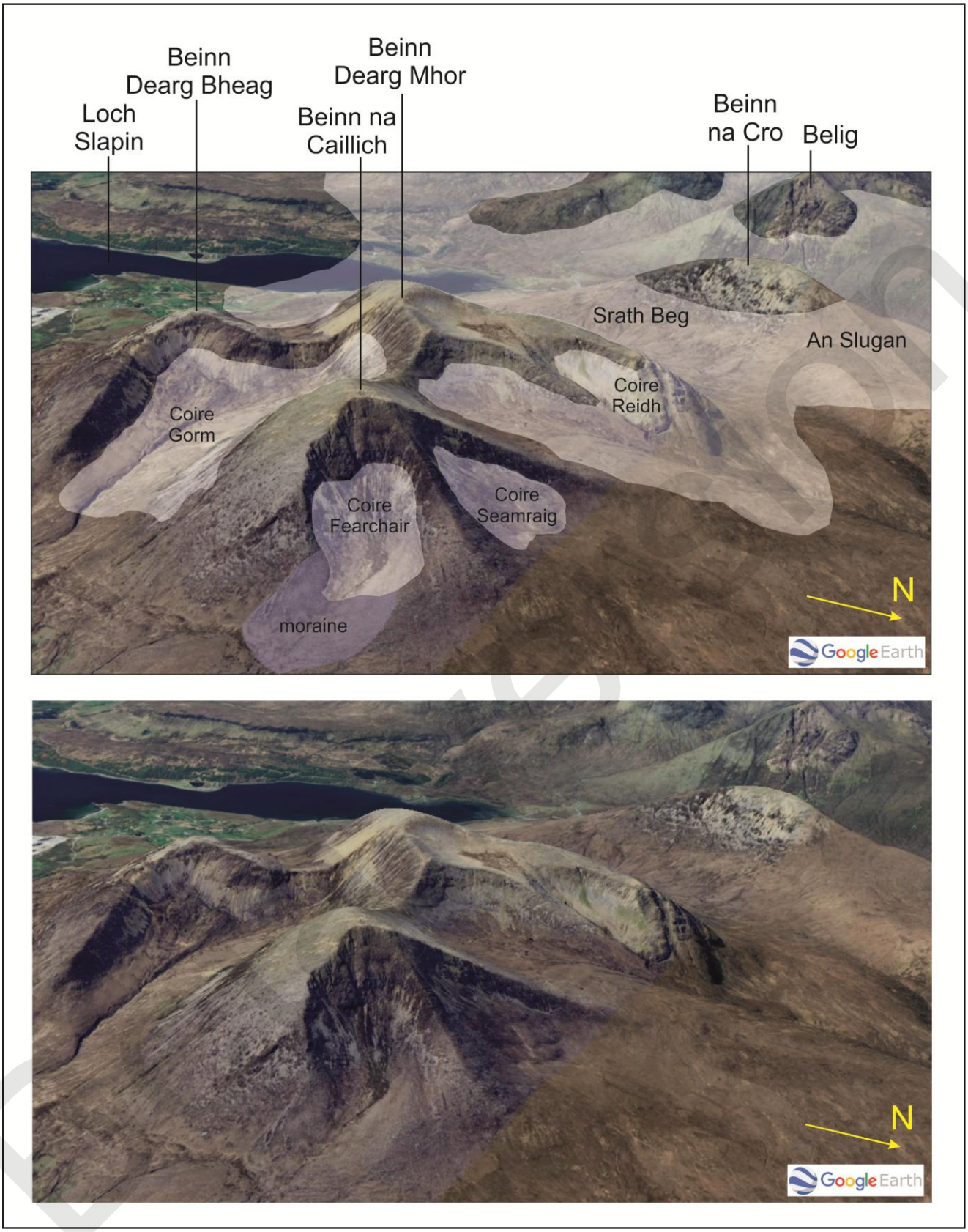


Figure 13-102: Oblique Google Earth© schematic image interpretation of the Loch Lomond Re-advance glaciers in the Eastern Red Hills, Skye.

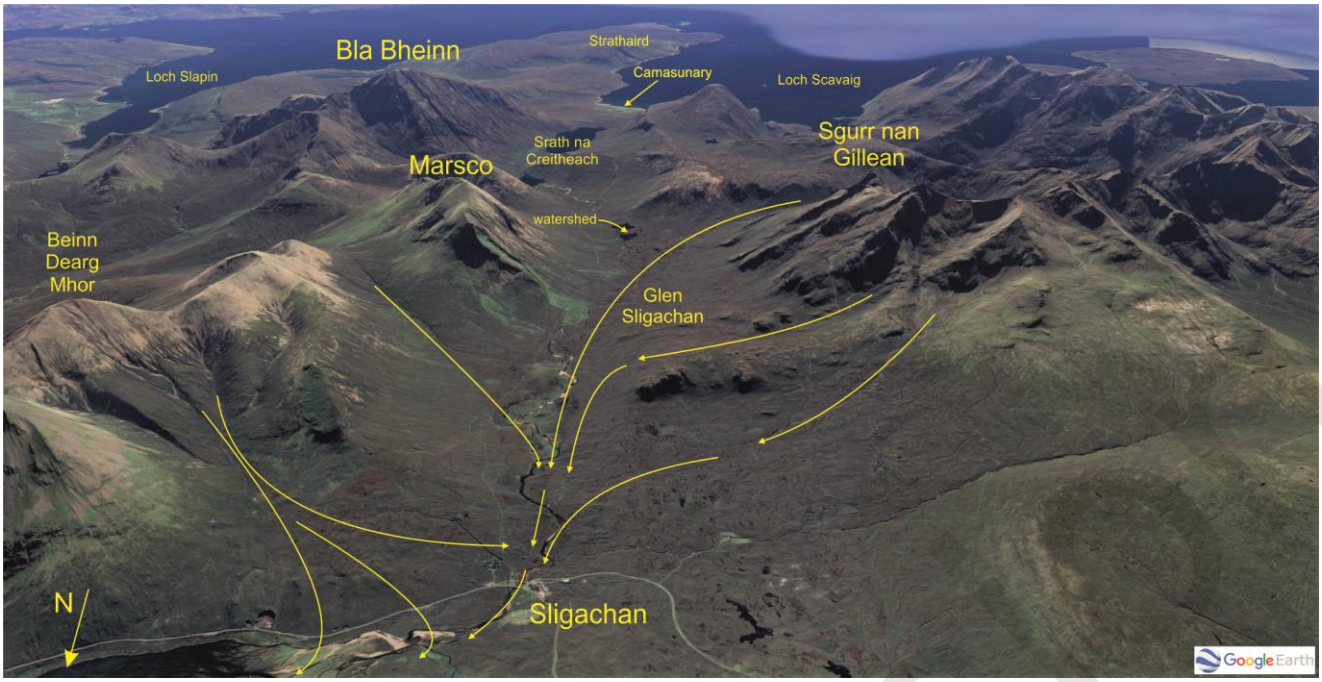


Figure 13-103: Oblique Google Earth© schematic image interpretation of the Glen Sligachan (Loch Lomond Re-advance) glacier pathways (arrowed), Skye.



Figure 13-104: Moraine deposits north of the Allt Daraich, Glen Sligachan, Skye. View towards the west.

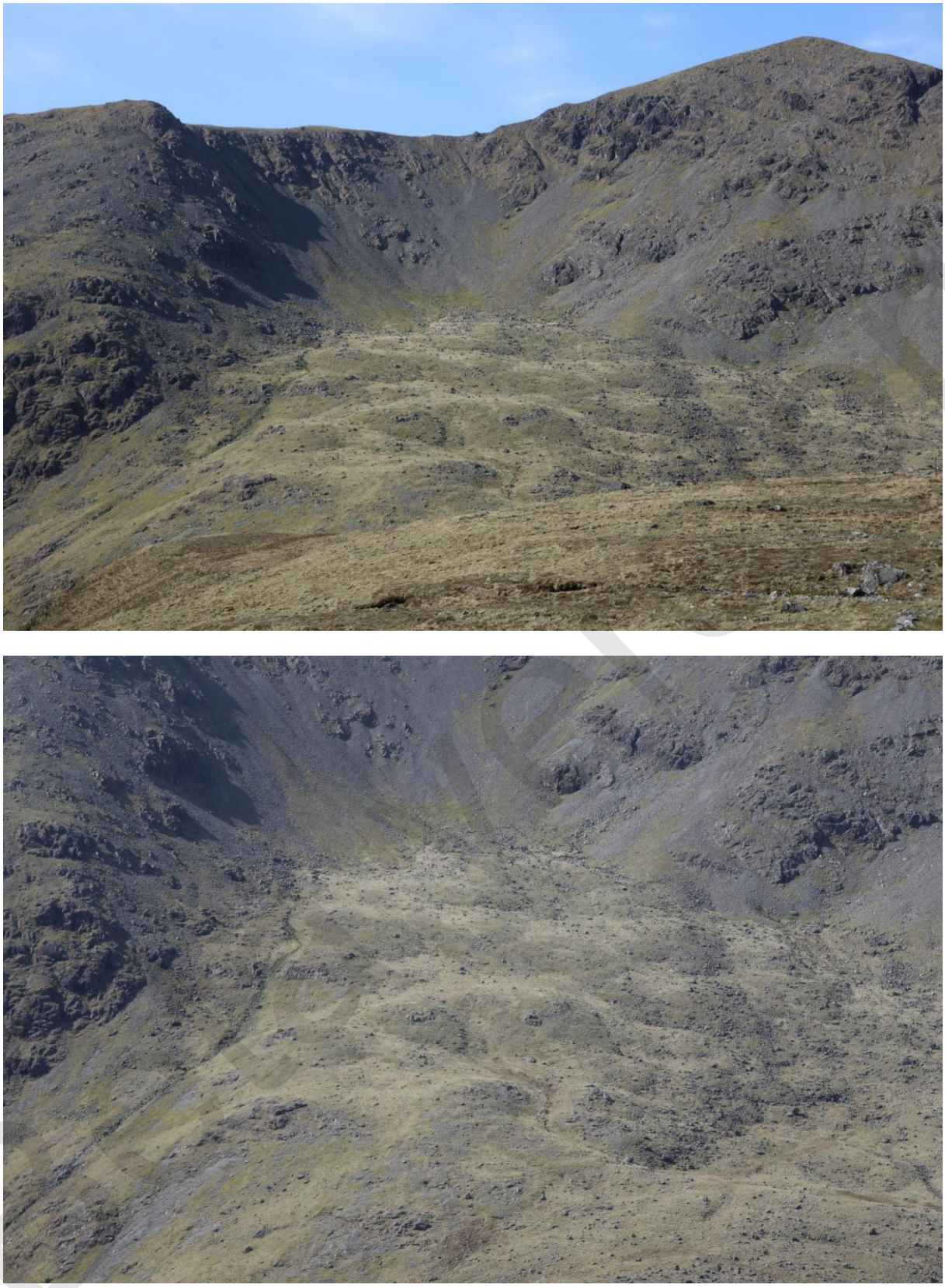


Figure 13-105: Hummocky moraine in unnamed corrie NE of Belig, Skye.

Depositional features from the Loch Lomond Stadial are abundant in the mountains in the southern half of Rum, where there is evidence that twelve local glaciers formed (Figure 13-106; Figure 13-107). One occupied Coire nan Gruund and, at the lower end of the corrie, the Kinloch - Dibidil Path, crosses a well-defined moraine made of ultrabasic blocks derived from the east side of Hallival and Askival. Rock slabs

north of the moraine preserve NNE-directed glacial striae from the Loch Lomond Stadial glaciation cutting across NW-directed striae from the earlier, Main Late Devensian Glaciation. In Upper Glen Harris, linear moraine ridges parallel to the direction of ice movement are strikingly developed in Atlantic Corrie.

A wealth of glacial erosional and depositional features is preserved on the Western Granite hills of Rum, including a fine arcuate terminal moraine composed of microgranite blocks north of Sron an t-Saighdeir. There is also a superb blockfield, of supposed Loch Lomond Stadial age, on the southern slopes of Orval and Sròn an t-Saighdeir (Ballantyne & Wain-Hobson 1980). This has been modified by later solifluction processes, with the development of stone stripes on the lower, steeper slopes.

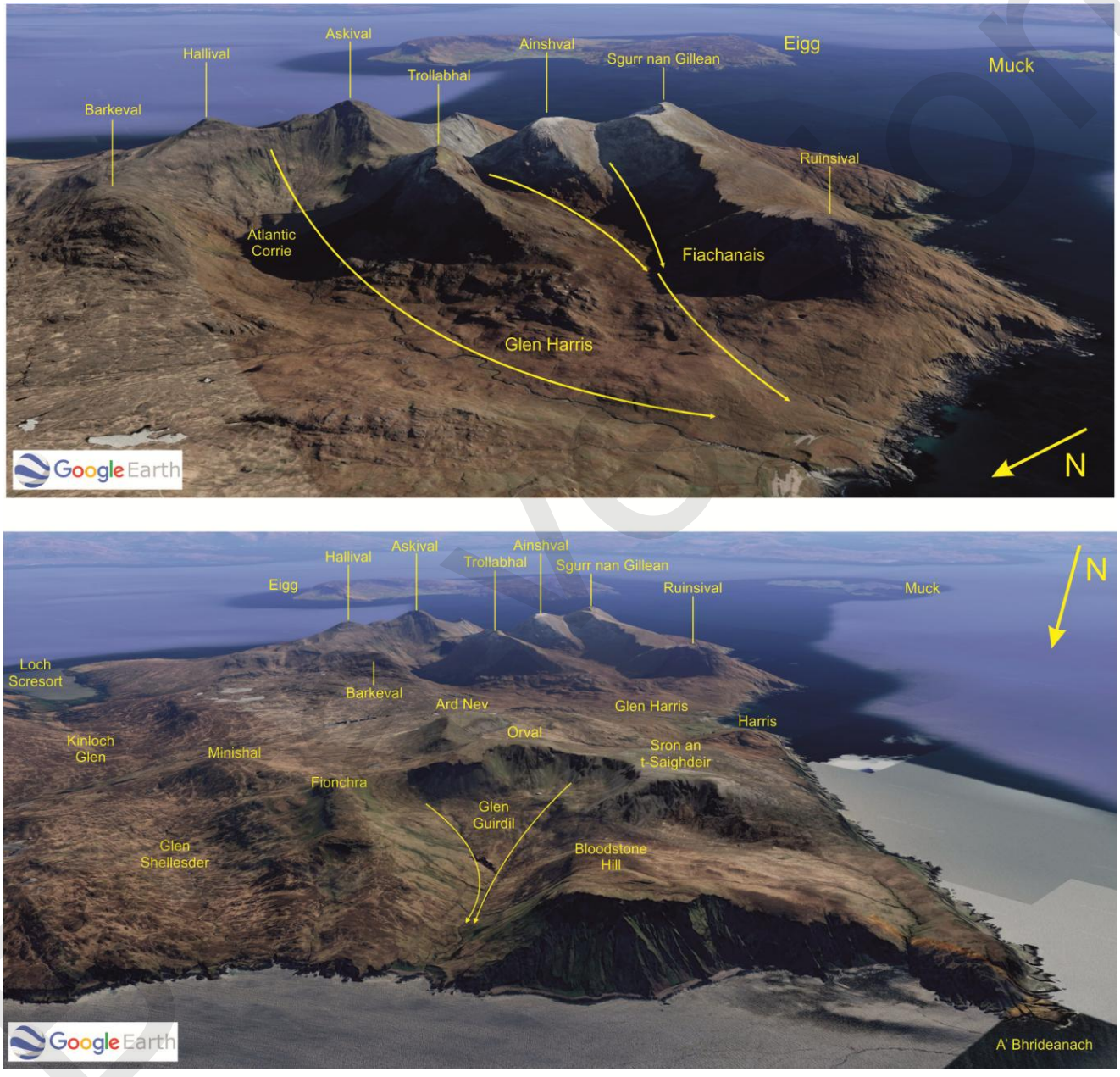


Figure 13-106: (a) Oblique Google Earth© schematic image (glacial pathway) interpretations of east and west Rum (Loch Lomond Re-advance) glaciers.

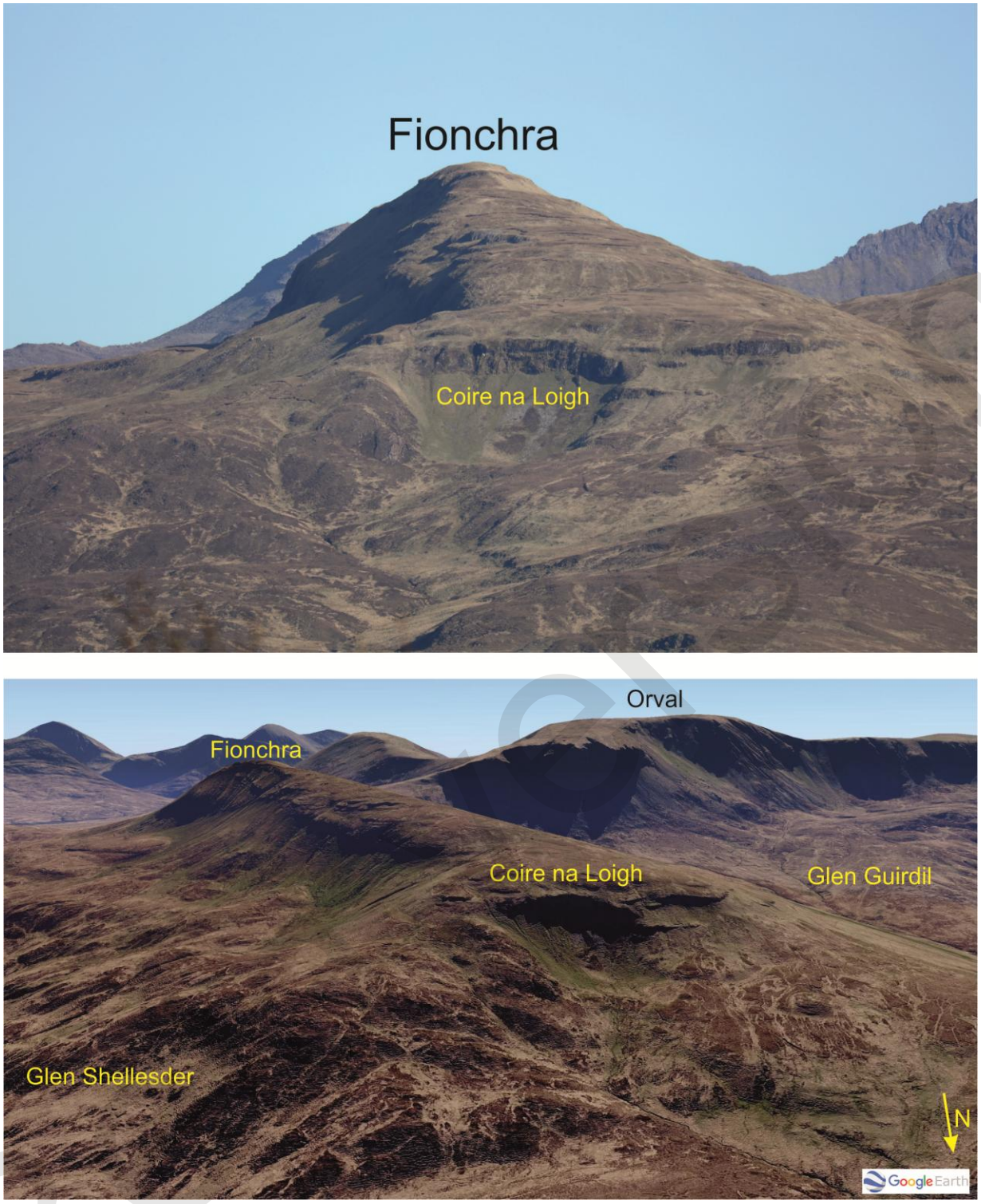


Figure 13-107: Oblique Google Earth© image and field photograph of Coire na Loigh at the NW end of the Fionchra ridge, NW Rum, formed during the Loch Lomond stadial.

During the Loch Lomond Stadial, Mull supported an ice sheet that extended from Loch Bà to Loch Spelve, with Beinn Talaidh and other high hills in central Mull forming nunataks (Figure 13-108). The most striking scenic features of Mull attributable to glacial processes date from this episode. Glaciers from the main area of ice reached the sea at several points, as did local glaciers flowing NNE off the hills into the Sound of Mull in the vicinity of Craignure. Outwash deposits formed at the foot of Loch Bà and Glen Forsa. Terminal moraines are present at Kinlochspelve and at the northern end of Loch Don, where Late-glacial deltaic deposits of the Loch Don Sand Moraine (see above) are partly covered by till from the Loch Lomond

Stadial glaciation (Benn & Evans 1993). Inland, there are widespread deposits of hummocky morainic drift, for example east of Craig in Glen More (Figure 13-108; Figure 13-109). Linear drift deposits, or fluted moraines, occur at several localities; well-defined examples on the NW shoulder of Sgùrr Dearg were formed by glaciers converging to the NW.

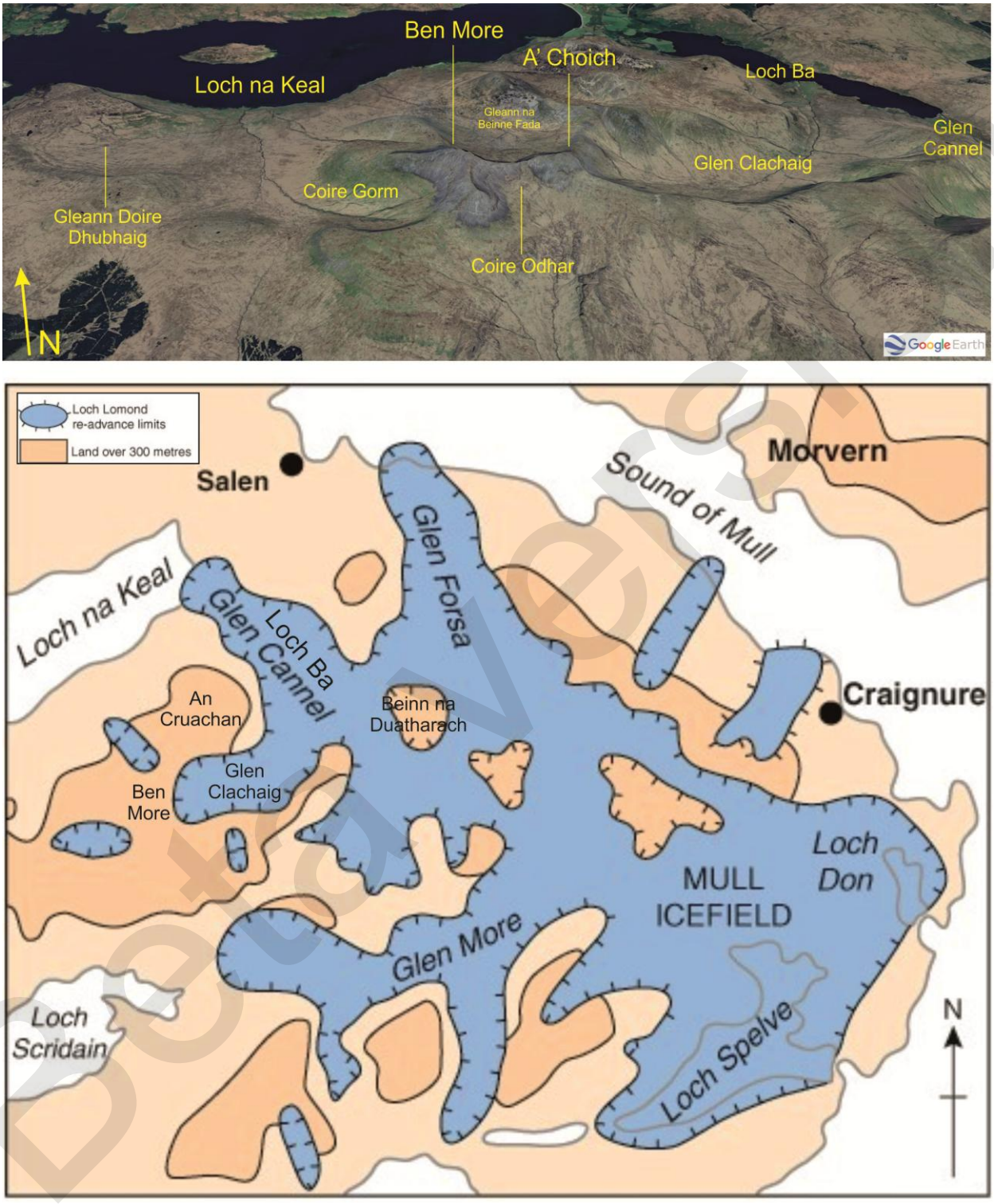


Figure 13-108: (a) Classic glaciated terrain of south-central Mull, with corries, ridges (arêtes) and arête pinnacles (pyramidal peaks, horns). Oblique Google Earth© image, view towards the SW; and, (b) interpretation of causal Loch Lomond Readvance glaciers (after Benn *et al.*1992).

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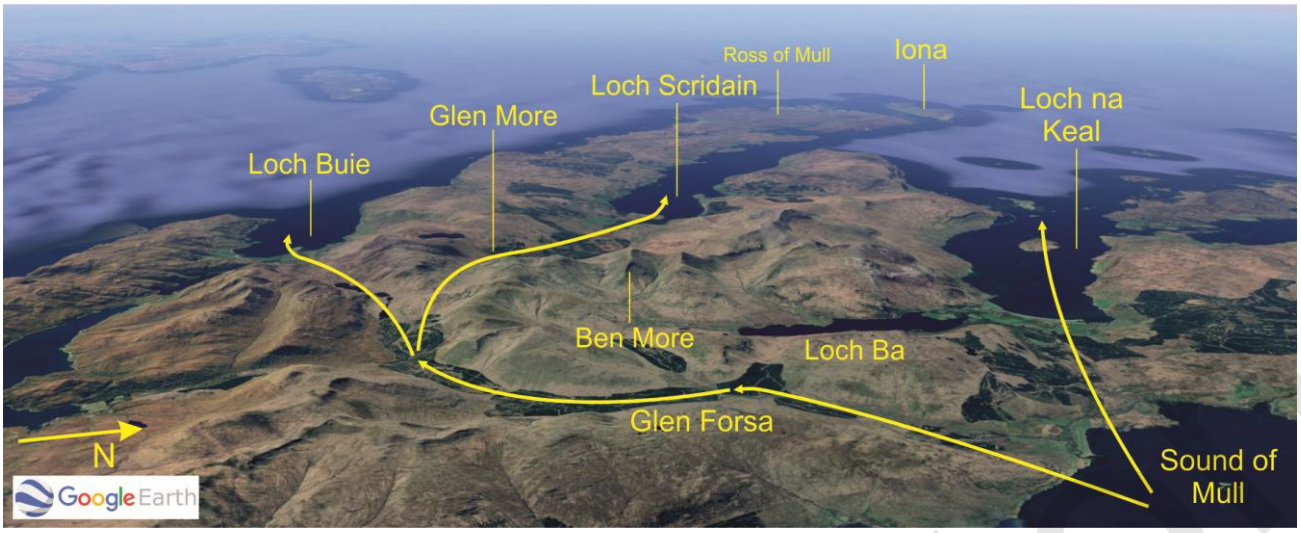


Figure 13-109: Oblique Google Earth© Image of possible Scottish Mainland ice flow paths, south-central Mull. View towards the SW.

The northern hills of Arran supported valley glaciers during the Loch Lomond Stadial and the till formed at this stage augmented earlier till (see above) (Figure 13-110; Figure 13-111; Figure 13-112; Figure 13-113; Figure 13-114; Figure 13-115; Figure 13-116; Figure 13-117; Figure 13-118; Figure 13-119; Figure 13-120). Valley glaciers from a small ice field centred on the head of Glen Iorsa extended down glens Catacol, Easan Biorach and Iorsa. Glaciers also occupied North Glen Sannox and the upper parts of glens Rosa and Sannox. Small corrie glaciers formed on the eastern side of the Goatfell ridge and NW and north of Beinn Bharrain. There are two generations of moraine in the northern hills. One group of well-defined moraines occurs at low levels throughout the area and is covered with grass and heather, for example in lower Glen Rosa. The second group is formed of fresh moraine ridges, studded with boulders and relatively free of vegetation. The latter moraines generally occur above 450 m OD and are almost entirely restricted to corries to the east of the northern hills, for example at the head of Glen Rosa, on the north side of Casteal Abhail, and to the SE of Beinn Tarsuinn. Substantial corrie glaciers evidently persisted in the eastern part of the northern hills after most of the ground to the west had become free of ice.

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Figure 13-110: The glacially sculpted topography of north Arran, viewed towards the SE from Caisteal Abhail. [Photograph courtesy of Richard Cross]

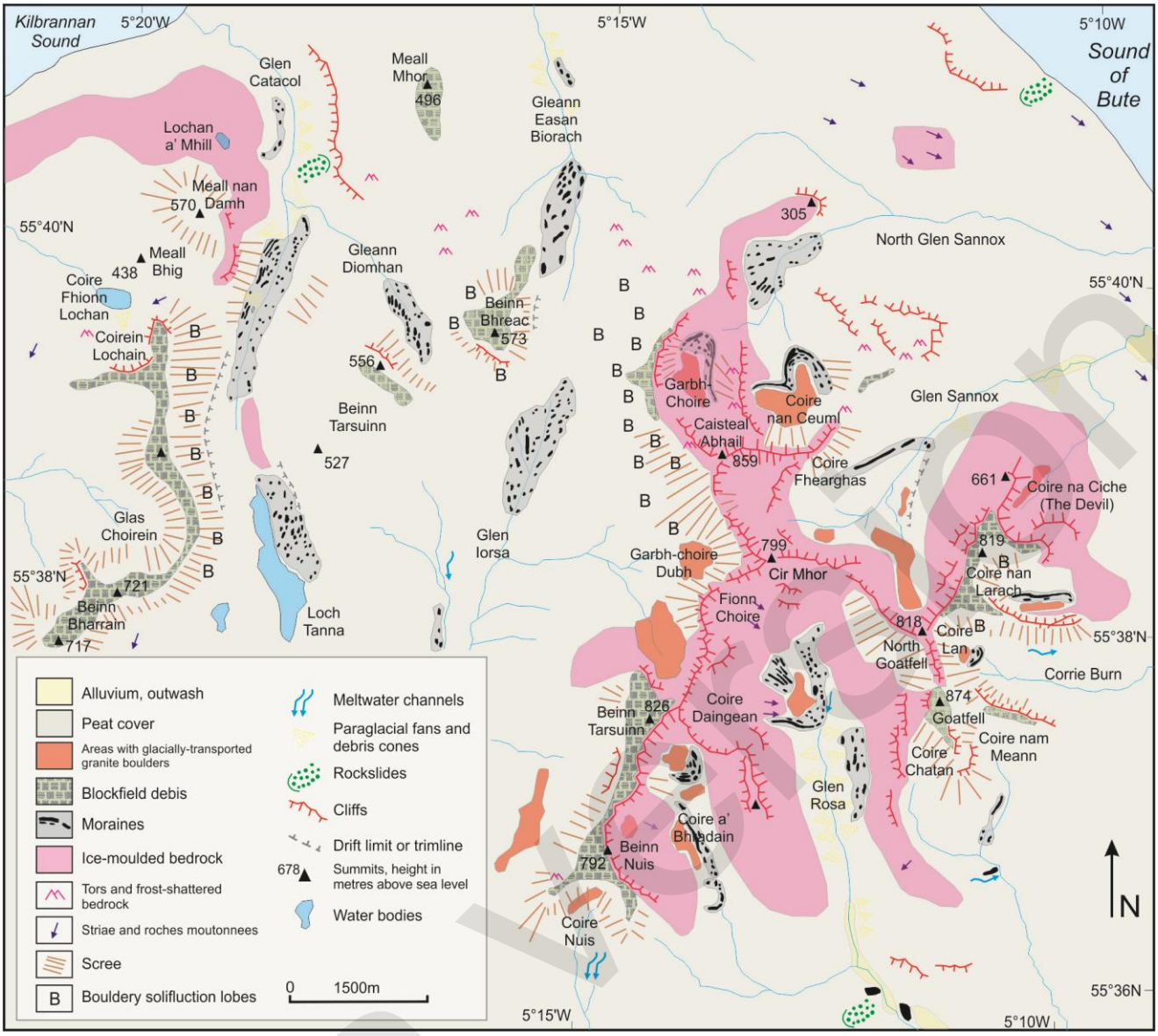


Figure 13-111: Geomorphological map of north Arran (after Ballantyne 2006).

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Figure 13-112: Stratified moraine deposits, Loch Garbad, south Arran.



Figure 13-113: Stratified moraine deposits, Loch Garbad, south Arran.



Figure 13-114: Unstratified ('massive') moraine deposits, Loch Garbad, south Arran.

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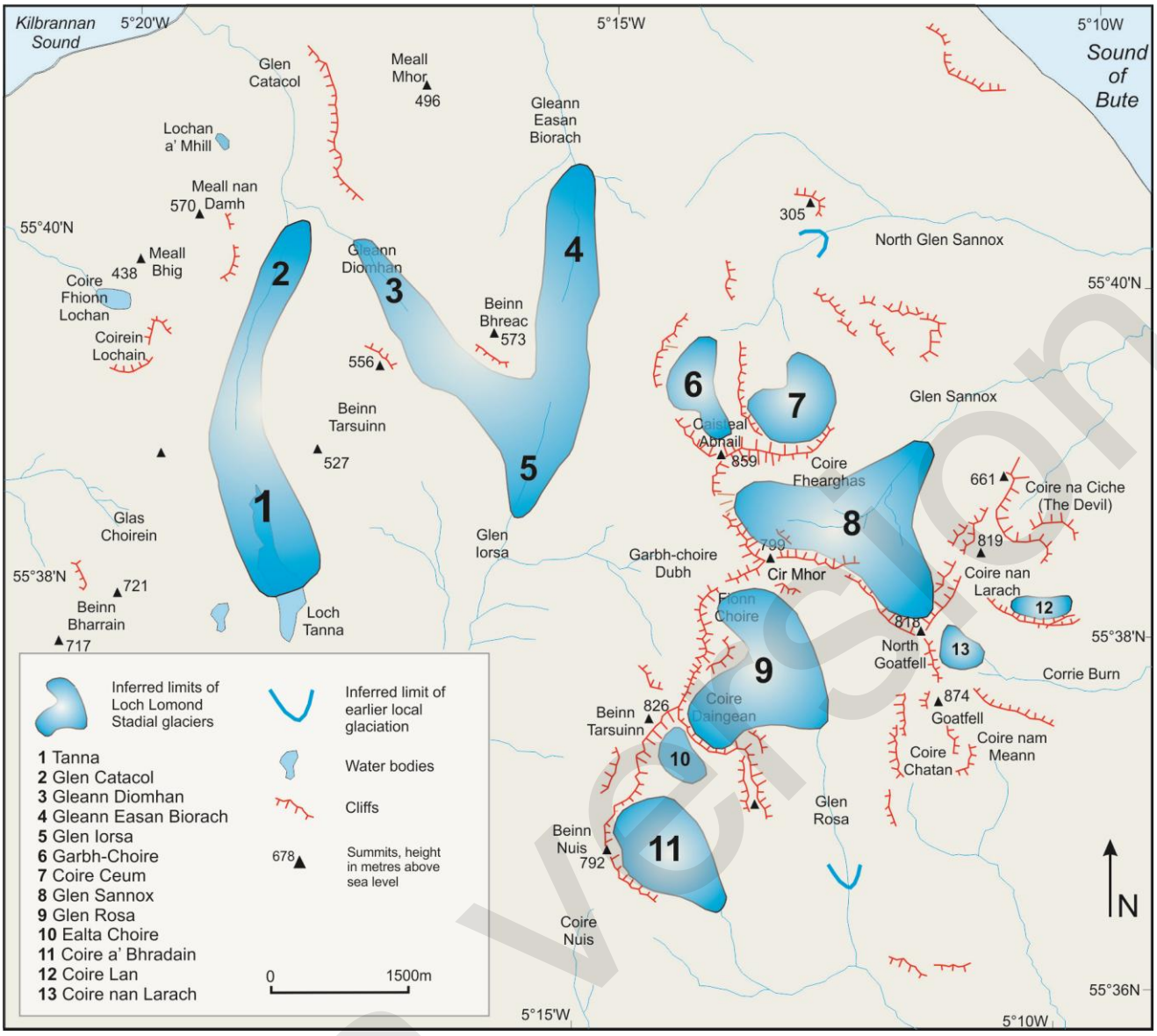


Figure 13-115: Reconstruction of the dimensions of inferred Loch Lomond Stadial glaciers in north Arran. Inferred limits of earlier valley glaciers in Glen Rosa and north Glen Sannox are also shown (after Ballantyne 2006).

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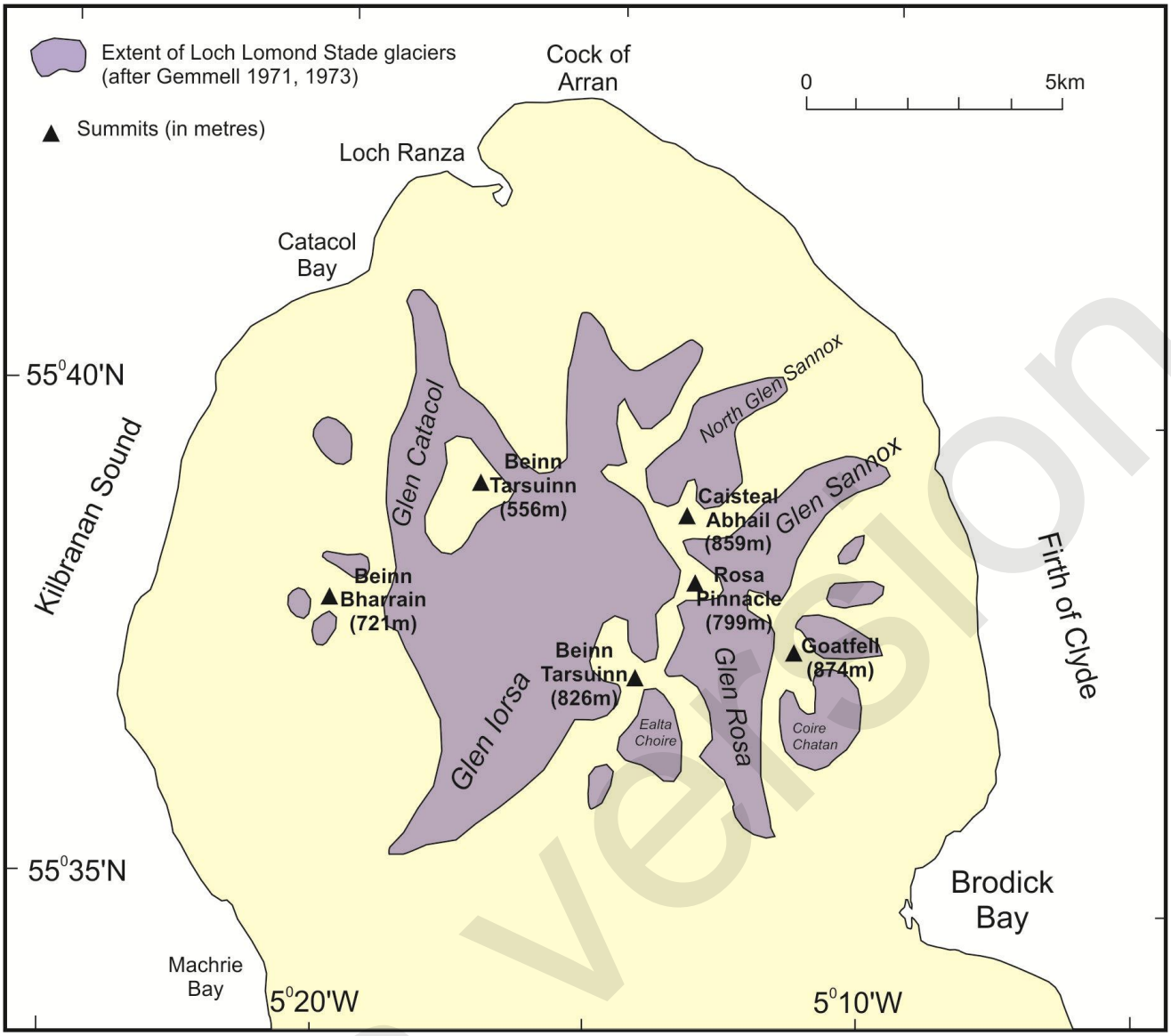


Figure 13-116: Limits of local ice fields on Arran during the Loch Lomond (or Younger Drias) Stadial (or glacial readvance) at *ca*. 12.9 ka – *ca*. 11.7 ka (after Ballantyne 2006).

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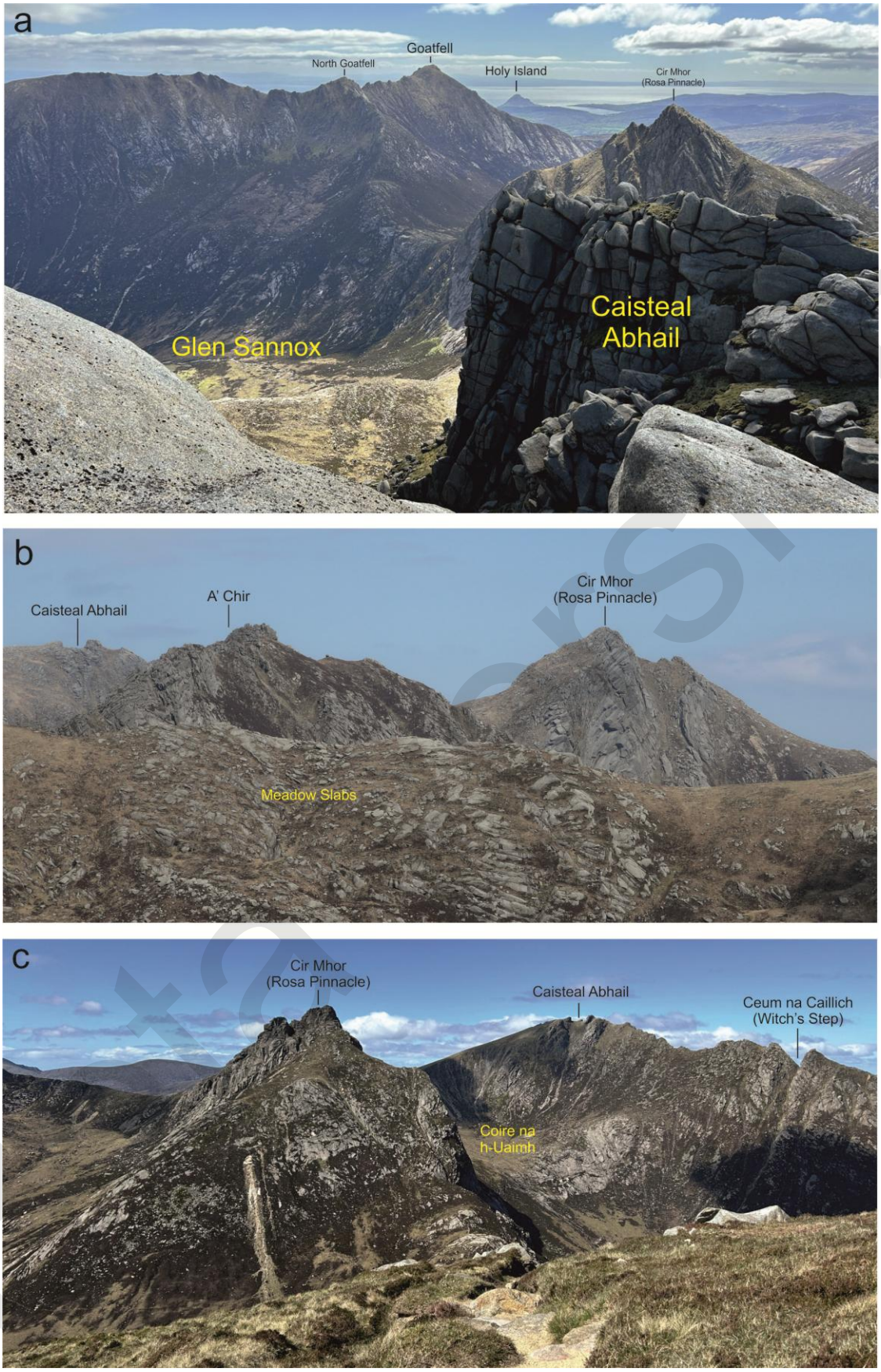


Figure 13-117: The glacially sculpted topography of north Arran, with classic arêtes, corries and pyramidal peaks.

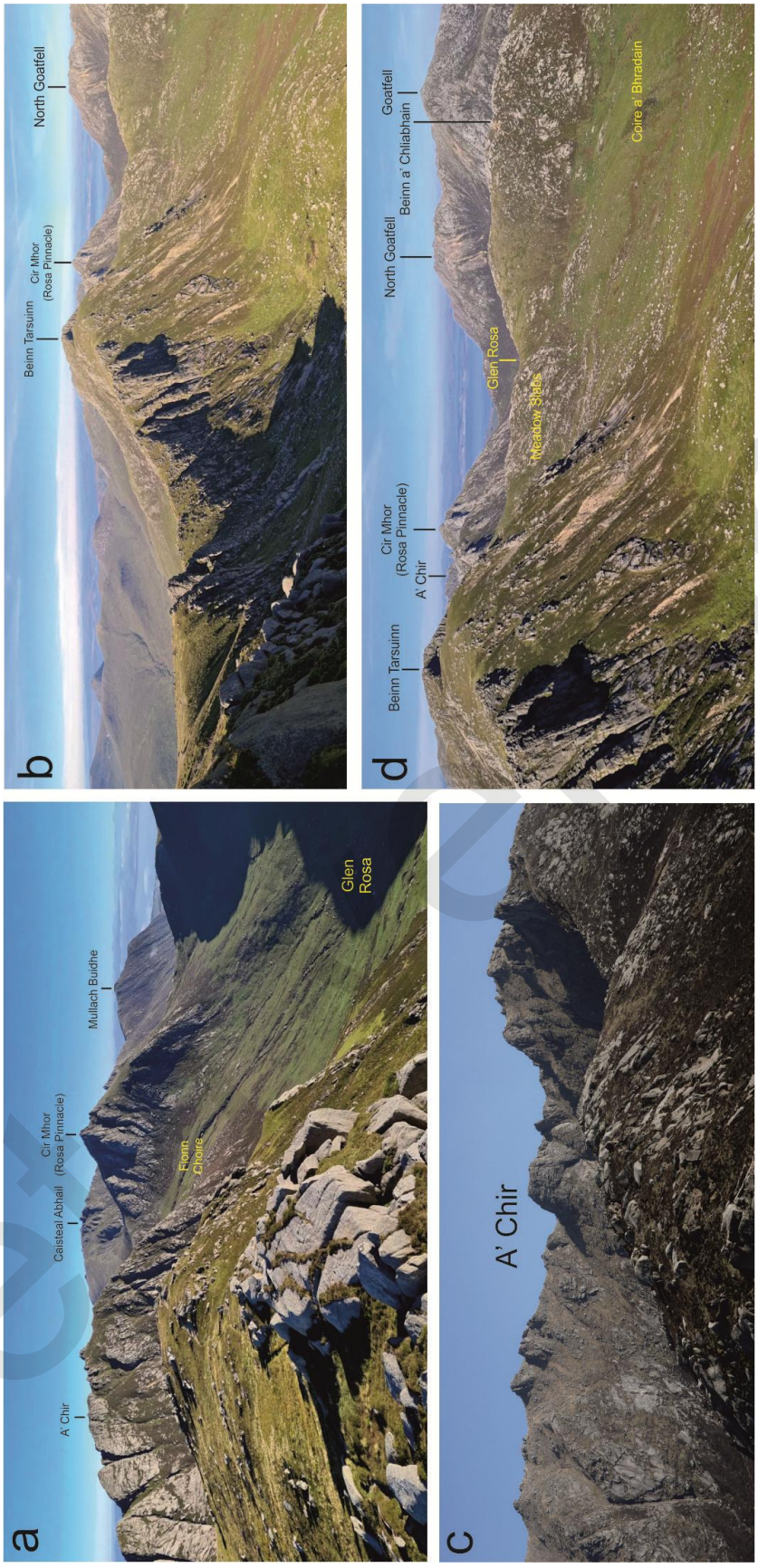


Figure 13-118: The glacially sculpted topography of north Arran, with classic arêtes, corries and pyramidal peaks.

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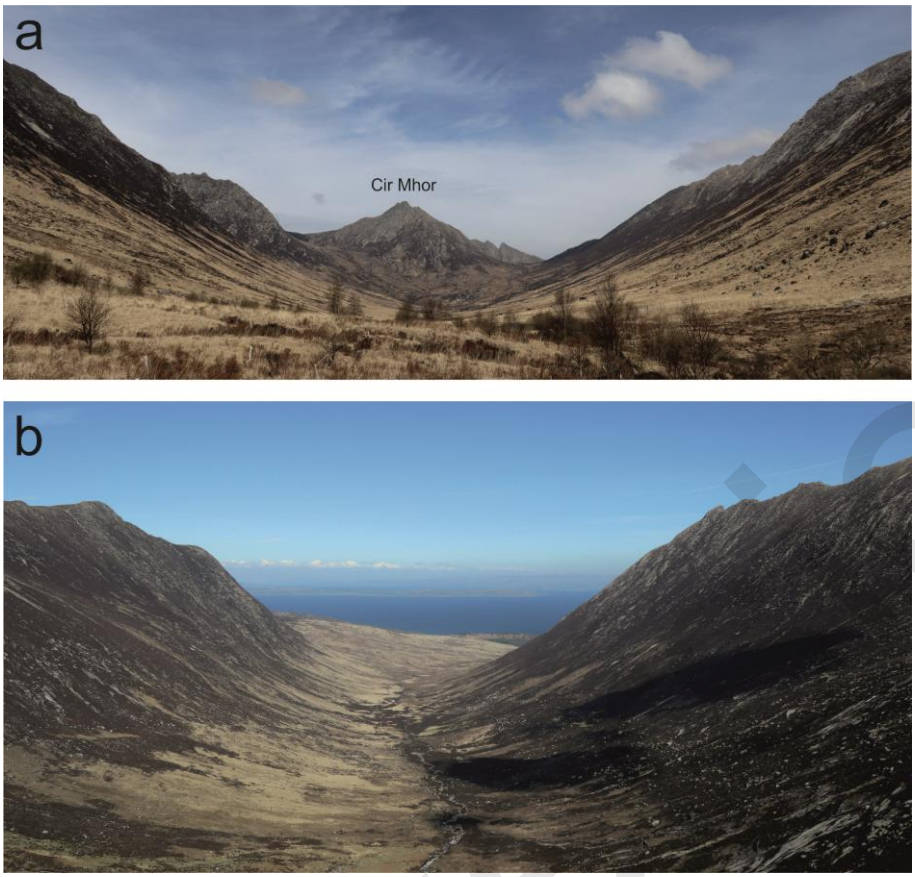


Figure 13-119: Views of the classic U-shaped glacial valleys of: (a) Glen Rosa (towards the north), and, (b) Glen Sannox (towards the NE).



Figure 13-120: Detail of the glacially sculpted granite slabs of The Bastion, Cioch na h-Oighe, NE Arran.

Periglacial deposits are widespread on St Kilda (see above). Hill slopes are mantled by frost-shattered debris, together with inactive solifluction lobes (Figure 13-121). Two major protalus ramparts north and west of Village Bay overlie the youngest till. Based on the relative freshness of the clasts and their

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stratigraphical relationships, the protalus ramparts are thought to have developed during the Loch Lomond Stadial, the last time that severe cold affected St Kilda.

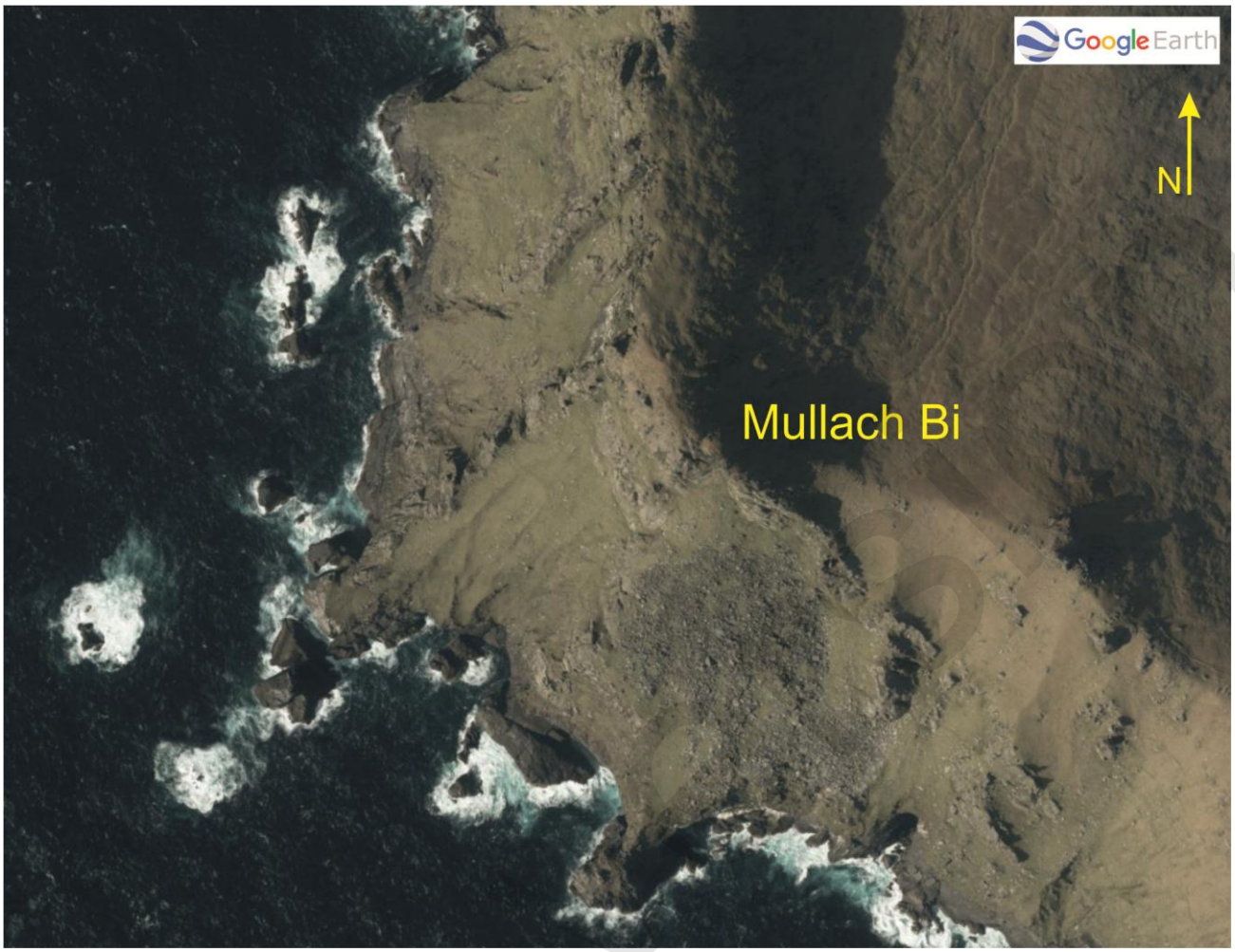


Figure 13-121: Frost shattered debris at Mullach Bi, Hirta, St Kilda.

13.9 Sea level changes

During the Quaternary glaciations, the weight of ice over Scotland caused isostatic depression of the land surface, while sea levels were lowered as water became locked up in the major continental ice sheets. When the ice melted in Late Glacial and postglacial times these processes were reversed, but isostatic recovery of the land initially lagged behind the eustatic rise in sea level, with the result that beaches and features of marine erosion were formed well above the present sea level. As isostatic recovery continued (and relative sea level fell), these features were uplifted to become raised beaches and wave-cut platforms (Figure 13-122). The amount of isostatic recovery was greatest over those areas where the ice had been thickest, with the result that initially horizontal raised marine features have been tilted. Since older shorelines will also have been affected by later events, their gradients tend to be steeper than those of the younger shorelines. Tilting is directed away from the centre of uplift, and ice distribution, which was in the vicinity of Rannoch Moor.

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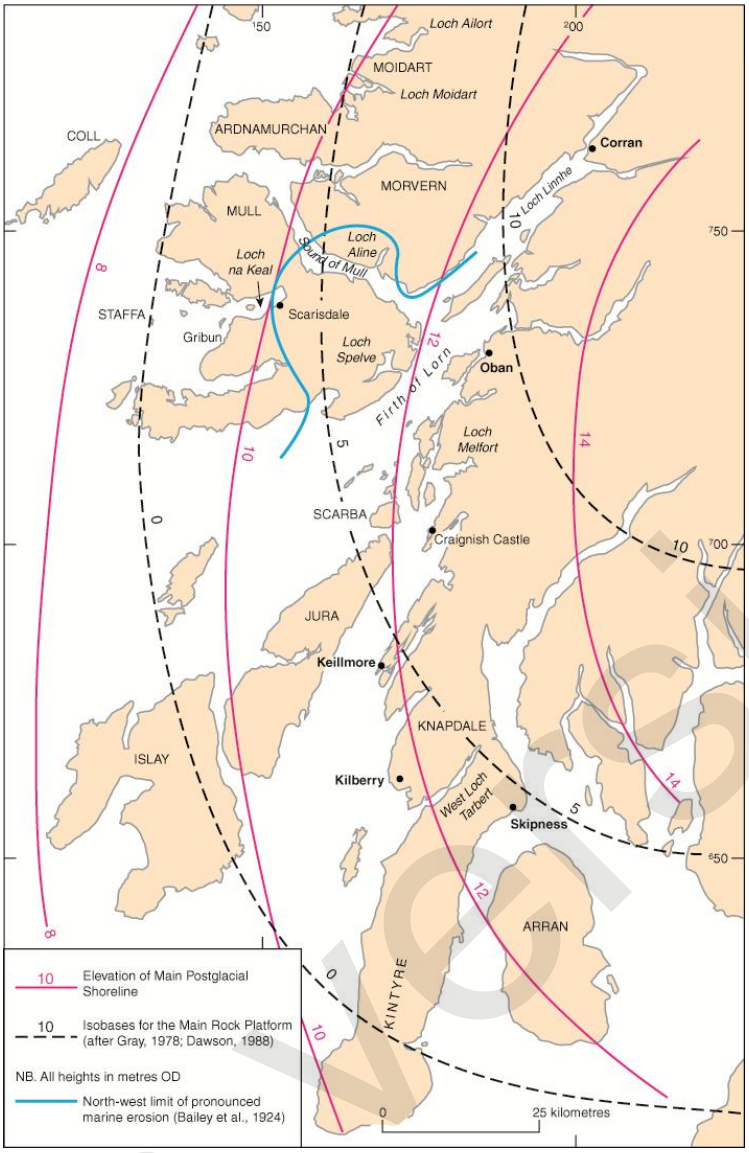


Figure 13-122: Isobases (in metres, OD) for the Main Rock Platform (MRP) in western Scotland (based on Gray 1989, Figure 1). The solid blue line represents the NW limit of pronounced erosion, identified by Bailey *et al.* (1924).

Several groups of coastal features attributable to relative sea level change are recognised within the district, although establishing their age remains problematic. This is particularly true in the Inner Hebrides and on Arran, where fossiliferous deposits suitable for independent dating are rare, and direct stratigraphic evidence is often lacking. In such contexts, the degree and pattern of glacio-isostatic tilting can provide a broad framework for relative chronology. However, tilting alone does not yield unequivocal age constraints because it may vary locally due to differential uplift, lithological variation, and the influence of postglacial faulting.

Correlation of rock-platform fragments is especially challenging in areas underlain by gently dipping sedimentary rocks or successive lavas. Over short distances, platforms may display gradual elevation increases interrupted by local falls, followed by renewed rises as erosion encounters beds of contrasting resistance. Such undulating or stepped surfaces may reflect variations in lithological strength rather than distinct former shorelines, complicating attempts to correlate discrete fragments across the coast. The lava benches around Treshnish Point, Mull, provide a clear illustration of this effect (Walker *et al.* 1992) (Figure 13-123). Here, sequences of basaltic lavas of variable thickness and erosional resistance produce

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irregular platform profiles, with individual benches rising and falling over short distances, making it difficult to identify continuous former sea levels.

These lithological and structural controls mean that a single 'platform' may not represent a single palaeo-shoreline but instead the product of combined processes: glacio-isostatic uplift, lithological variation, and marine erosion. Consequently, detailed field mapping, coupled with observations of platform morphology, cliff backing, and marine deposits where present, is required to reconstruct relative sea level histories. While such features offer important insights into Holocene and Late Glacial sea level changes, their interpretation must always account for local complexity and the potential for miscorrelation, particularly in basaltic terrains such as Mull and the Inner Hebrides more generally.



Figure 13-123: Lava bench, Treshnish Point, NW Mull.

13.10 Late-glacial shoreline deposits

The higher raised beach deposits were formed during the retreat of the Main Late Devensian ice sheets (Figure 13-2), when there was much sand and gravel being transported by meltwater. These gravel-rich deposits occur up to *ca*. 30 m OD. Late-glacial raised beaches at lower levels have been identified on Skye, where they are generally restricted to sheltered shorelines and the mouths of certain lochs. On the north side of Staffin Bay, near Digg, Late-glacial gravel deposits rest on a high rock platform at *ca*. 18 m OD, and in southern Skye terraced raised beach deposits are well developed between Broadford and Kyleakin, where they are quarried (Chapter 14) (Figure 13-124; Figure 13-125; Figure 13-126; Figure 13-127; Figure 13-128). The altitude of the higher raised beach deposits falls westwards from *ca*. 30 m OD at Kyleakin to *ca*. 15 m OD at Loch Harport, with a gradient of *ca*. 0.4 m per kilometre. This shoreline, now tilted by variable isostatic recovery, reflects the maximum sea level around Skye during retreat of the Main Late Devensian ice sheet. High raised beaches (over 15 m OD) do not occur within the areas affected by glaciers of the Loch Lomond Stadial; for example, they are absent from Loch Ainort and from Loch Sligachan. The contrast between Late-glacial and postglacial beach levels may be observed east of Strollamus, Skye. Late-glacial beach sands and gravels occur at over 23 m OD, close to the eastern margin of the former (Loch Lomond Stadial) Strath Beag Glacier, whereas postglacial beach gravels deposited against the moraines from this glacier are at 7 m OD.

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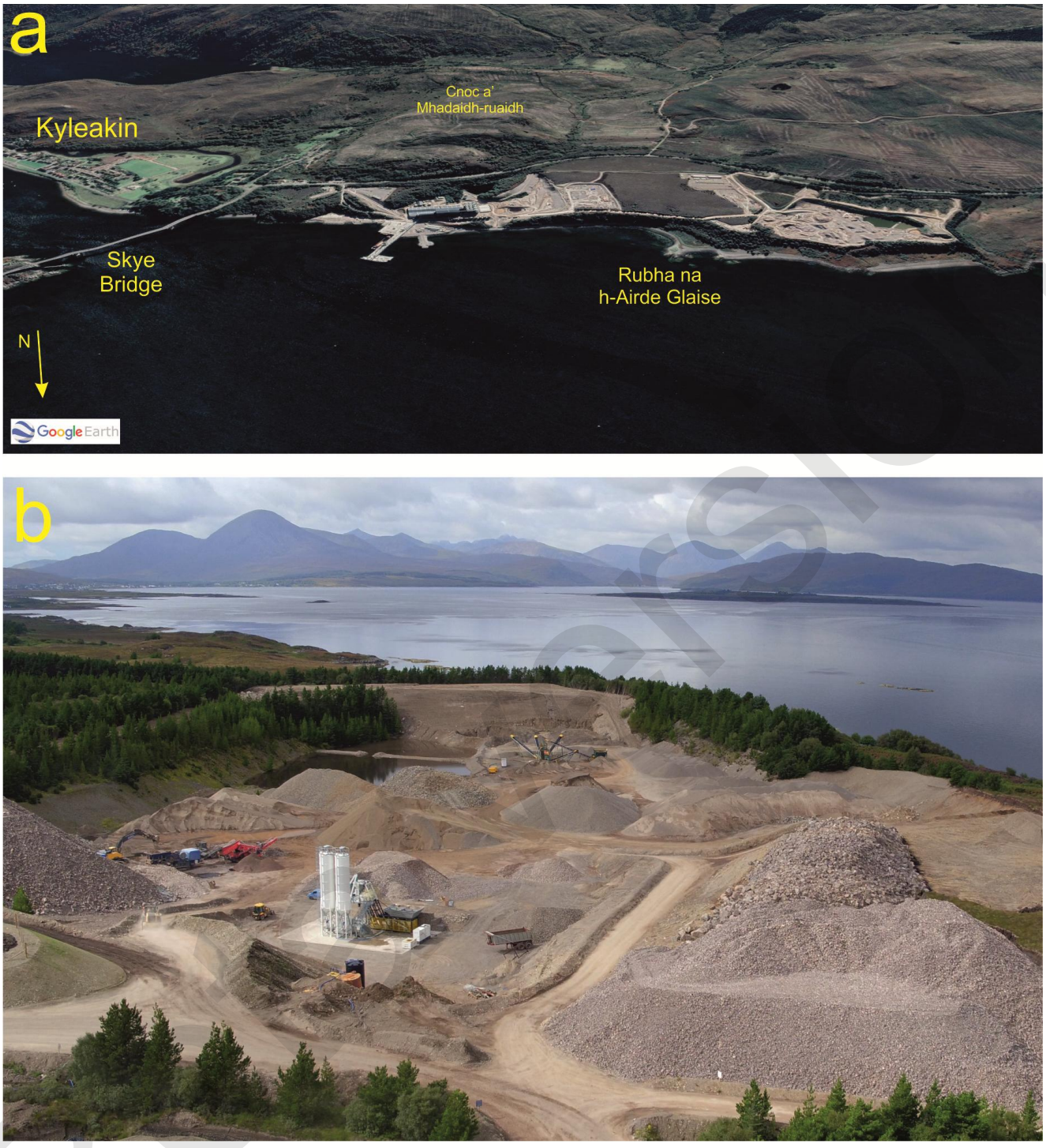


Figure 13-124: Late-glacial gravel deposits on a high rock platform at Rubha na h-Airde Glaise, west of Kyleakin, Skye.



Figure 13-125: Detail of Late-glacial gravel deposits on a High Rock Platform (HRP) at Rubha na h-Airde Glaise, west of Kyleakin, Skye. Note ice moulded bedrock (Torridonian sandstone) below gravels (bottom-right) and overlying peat deposits (top-right).

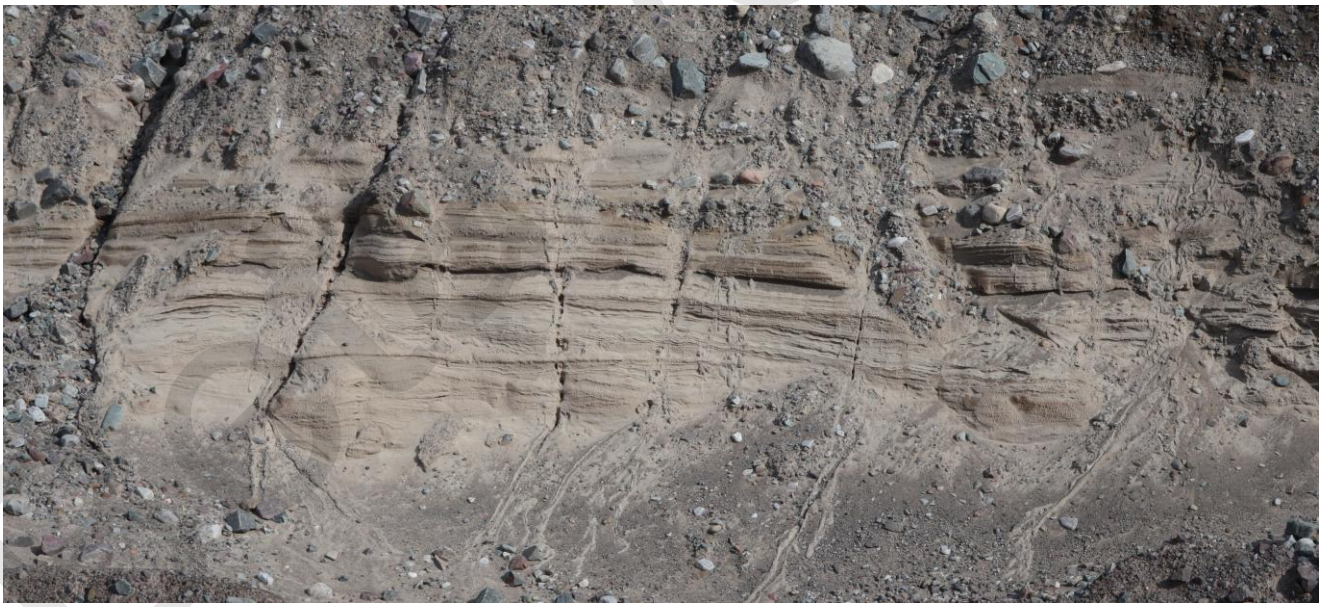


Figure 13-126: Detail of sands in Late-glacial deposits on a High Rock Platform (HRP) at Rubha na h-Airde Glaise, west of Kyleakin, Skye.



Figure 13-127: Detail of Late-glacial gravel deposits on a High Rock Platform (HRP) at Rubha na h-Airde Glaise, west of Kyleakin, Skye.



Figure 13-128: Ice moulded bedrock (Torridonian sandstone) below gravels at Rubha na h-Airde Glaise, west of Kyleakin, Skye.

Late-glacial raised beach deposits are present on all of the Small Isles (Figure 13-129; Figure 13-130; Figure 13-131). Late-glacial, storm-deposited shingle ridges rise to *ca*. 30 m OD at Harris on Rum. Storm beaches from this period are also present at similar heights above sea level at Tarbert on Canna (21 m), Camas Mór on Muck (30 m) and Camas Sgiotaig on Eigg (25 m).



Figure 13-129: Late-glacial, storm-deposited raised beach deposits, Harris Bay, SW Rum.



Figure 13-130: Late-glacial raised beach deposits, Bay of Laig, west Eigg.



Figure 13-131: Late-glacial raised beach deposits, Bay of Laig, west Eigg.

Raised, marine-cut benches occur at several levels around Mull and on Morvern. On Mull, the highest (at *ca*. 30 m OD) and one of intermediate level (at *ca*. 20 m OD) are covered by deposits attributed to glaciers

of the Loch Lomond Stadial and hence predate that event. This relationship can also be demonstrated at the lower ends of Glen Cannel (Loch Bà) and of Glen Forsa, where outwash deposits associated with glaciers from the Loch Lomond Stadial are not cut by, and hence postdate, marine notches that are present in adjacent coastal exposures.

Raised beaches were formed on Arran when ice from the Highlands covered the north of the island (Figure 13-132). The highest altitude, at *ca*. 33 m OD, occurs at Imachar on the west coast. Outwash deposits associated with a major glacier from this period in Glen Iorsa are cut by beaches at about 20 m OD (see below).



Figure 13-132: Raised beach platform, north of Machrie Bay, west Arran.

13.11 Main Rock Platform (MRP)

The Main Rock Platform is a particularly striking example of a well-developed marine shoreline eroded in rock. The height of the platform varies from over 10 m OD in the sea lochs NE of Oban and in the innermost lochs north of the Firth of Clyde, to below present day sea level in the west of Mull and south of Kintyre (Gray 1989). The clearest development of the platform is in the SW Highlands, including eastern Mull and Arran, though farther north, rock platforms on Skye and in other areas have also been correlated with the Main Rock Platform (MRP). The platform is generally broad and in places is over 200 m wide. Raised sea stacks may be present on the platform, which is commonly backed by relict sea cliffs.

The age of the MRP has been much debated (Walker *et al.* 1992). It was originally regarded as Holocene in age (e.g. Bailey *et al.* 1924), but subsequently it was pointed out that this would not allow enough time for cutting away of so much solid rock, and a preglacial or interglacial age was suggested (McCallien 1937).

Sissons (1974) argued that the platform was eroded mainly during the Loch Lomond Stadial under periglacial conditions.

The evidence favouring a Loch Lomond Stadial age includes: the unglaciated character of the platform in many areas; the surface defined by platform remnants is tilted at a gradient between that typical of the early Late-glacial shoreline and that of the early Holocene shoreline; postglacial shorelines; and, erosion of the platform in some very resistant rocks in sheltered locations where frost riving could have been much more effective than normal coastal erosive processes.

Evidence against formation during the Loch Lomond Stadial includes: undoubted marine coastal erosional landforms are commonly present, for example sea stacks, caves and undercut cliffs; the preservation of delicate glacial features, such as striae and p-forms, would not be expected to have survived erosion during the Loch Lomond Stadial; the lack of angular debris in the offshore sediments, which would be expected to be present if there had been rapid erosion to form the platform during the Loch Lomond Stadial; and, a few pre-Holocene dates have been obtained that apparently constrain the age of the platform.

Remnants of the MRP are strikingly preserved on the coast around the Firth of Lorn (Walker *et al.* 1985). In eastern Mull, Duart Castle is built above the raised platform (Figure 13-133), at *ca.* 8 m OD, and both the platform and raised cliff, which is over 10 m in height in places, are present for several kilometres to the south (Figure 13-134). South of Loch Don, both the platform and the backing cliffs form prominent features, for example at Port Donain.



Figure 13-133: Duart Castle atop the Main Rock Platform, Duart Point, SE Mull.

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Figure 13-134: The Main Rock Platform, south of Duart Point, SE Mull.

Remnants of the MRP also occur in Ardnamurchan, and in Moidart they extend eastwards up to the limits of the Loch Lomond Readvance (Dawson 1988). The level of the platform in Ardnamurchan falls from *ca*. 2 m OD near Ockle on the north coast, to just above sea level at Ardnamurchan Point, a distance of *ca*. 15 km. There are several good examples of the wide (up to 500 m), ice-sculpted platforms backed by raised cliffs, for example south of Rubha Carrach on the north coast where raised sea caves, the 'Glendrian Caves', can also be seen (Figure 13-135; Figure 13-136). Coastal caves in south Eigg may have a similar origin ().



Figure 13-135: Main Rock Platform, Rubha Carrach, NW Ardnamurchan.

Beta version



Figure 13-136: Glendrian Caves, Rubha Carrach, NW Ardnamurchan.

The Main Rock Platform is extensively developed on Arran but tends to merge with postglacial shoreline features to form a single, low, raised shoreline around most of the island (Gemmell 1972), inaccurately termed the '25 foot raised beach' by earlier workers (e.g. Tyrrell 1928). Much of the coastal road has been built on the platform (Figure 13-137; Figure 13-138; Figure 13-139; Figure 13-140; Figure 13-141; Figure 13-142; Figure 13-143; Figure 13-144; Figure 13-145), for example north of Machrie, between Corrie and Brodick Bay, and west of Loch Ranza. North of Corrie, very large glacial erratics of granite derived from the Paleocene North Arran Granite Pluton (Chapter 9) rest on the platform. In NE Arran, the platform is at *ca*. 4.5 m OD, falling to *ca*. 2.1 m OD to the SE of Brodick and at Tormore on the west coast; it drops to 1.4 m near Kildonnan in the south of the island.



Figure 13-137: The Main Rock Platform, Dougrie coast, west Arran.

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Figure 13-138: The Main Rock Platform, King's Cave(s), west Arran.



Figure 13-139: Raised beach, Slidderywater Foot, SW Arran.

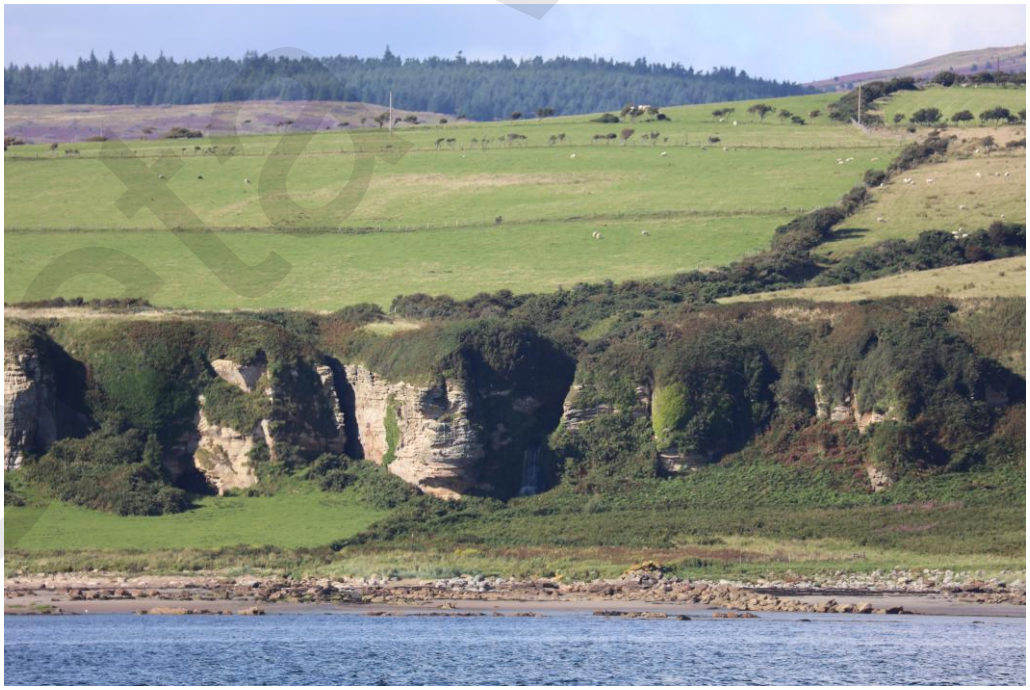


Figure 13-140: The Main Rock Platform, West Bennan, south Arran.

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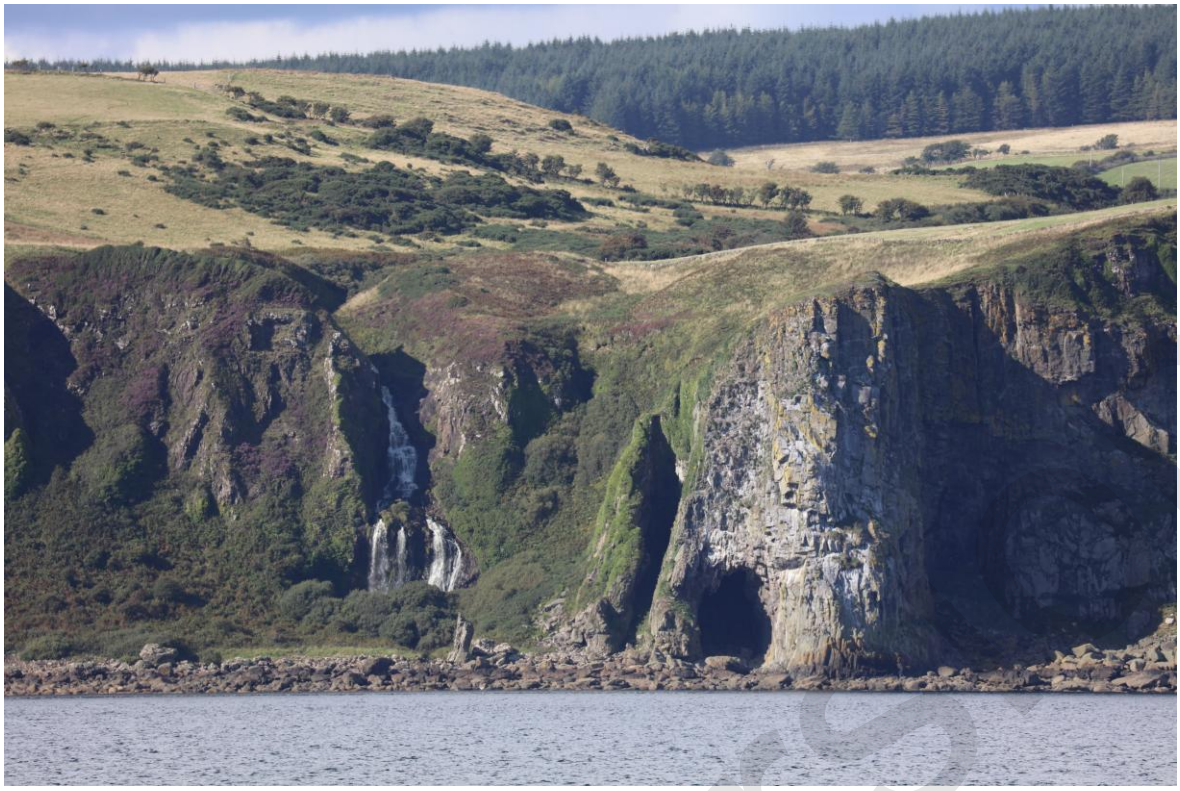


Figure 13-141: The Main Rock Platform, Black Cave, Struey Rocks, Bennan Head, south Arran.



Figure 13-142: The Main Rock Platform, Newton, Lochranza, north Arran.

Proof version



Figure 13-143: Corrie, NE Arran, constructed upon the Main Rock Platform.



Figure 13-144: Coastally eroded cliff at back of Main Rock Platform, Sannox, NE Arran.



Figure 13-145: Clach a' Chath (Cat Stone) granite erratic, atop the Main Rock Platform, between Sannox and Corrie, NE Arran.

Rock platforms below the level of the High Rock Platform (HRP) are present in eastern Rum and possibly on Canna and Eigg (Figure 13-146), but details are sparse. However, on Skye there are well-defined low rock platforms formed by marine erosion, for example for some distance north of Portree Harbour where the platform is at 2 to 7 m OD. The clearest examples, with geos, caves and stacks, occur on Sleat and on Strathaird, where the low rock platforms are at 0 to 5 m OD (Figure 13-147; Figure 13-148). The Low Rock Platform is also recognised in SW Rum (Figure 13-149). These occurrences may be the equivalents of the Main Rock Platform, which might be expected to be present at these levels in southern Skye (Ballantyne *et al.* 1991). The platforms appear to be absent from areas previously occupied by glaciers of the Loch Lomond Stadial.

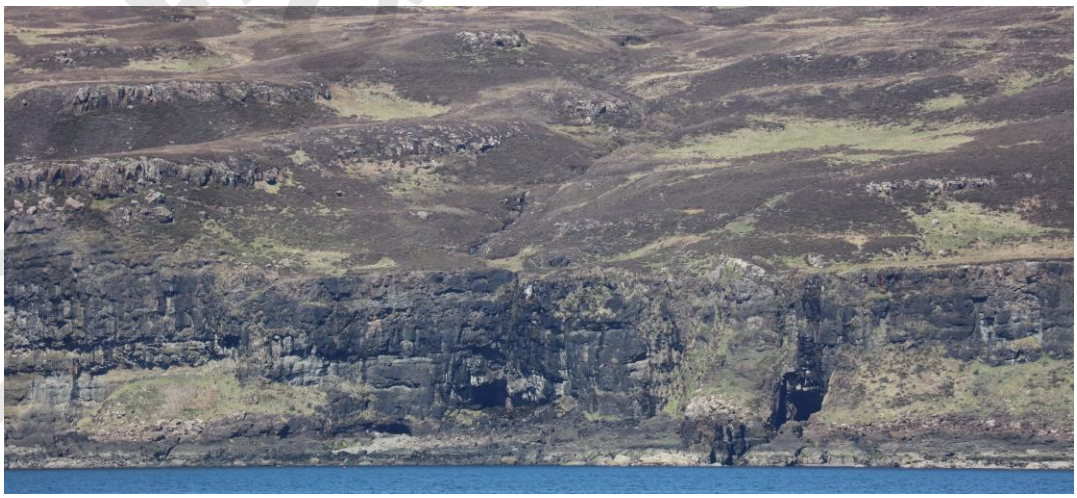


Figure 13-146: Sea caves, Uamh Chràbhaichd (Cathedral Cave, left) and Uamh Fhraing (Massacre Cave), south coast of Eigg.

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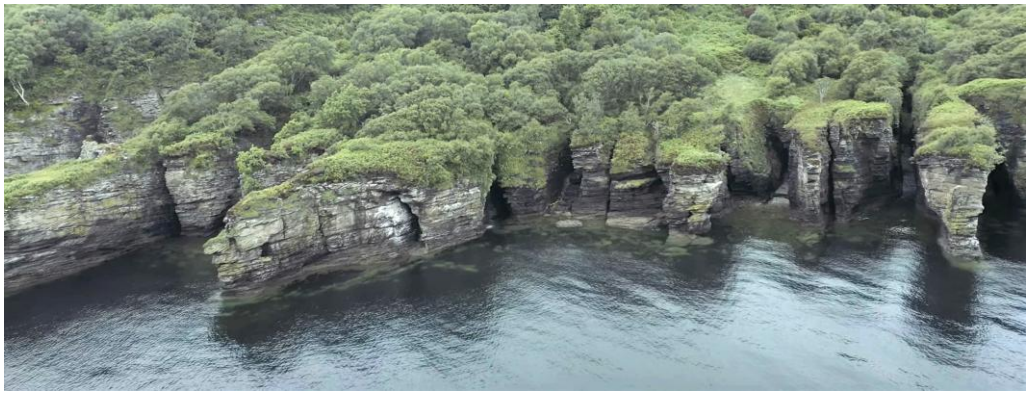


Figure 13-147: Low Rock Platform, east coast of Strathaird, south-central Skye.



Figure 13-148: Low Rock Platform, east coast of Strathaird, south-central Skye.



Figure 13-149: Low Rock Platform, SW Rum.

Beta Version

13.12 Postglacial shorelines

In the early Holocene (Figure 13-2), isostatic rebound of the land initially outpaced the rising sea level, and in general the evidence from Scotland is of falling relative sea level. However, between *ca*. 8,500 and 6,500-years BP, a major rise in sea level occurred which is attributed to the final melting of the ice sheet that covered much of North America (Walker *et al*. 1992). The widespread Main Postglacial Shoreline dates from this transgression (Figure 13-2).

Postglacial beaches on Skye are associated with a variety of features, including fossil shingle ridges and raised tombolos. The Main Postglacial Shoreline on Skye is tilted gently towards the NW (at *ca*. 0.07 m per kilometre), falling from *ca*. 10 m OD at Kyleakin in the SE to *ca*. 6 m OD at Duirinish in the NW. At Staffin Bay, the Main Postglacial Shoreline is marked by well-defined, vegetated shingle ridges at *ca*. 6 m OD; to the north, segments of this shoreline are cut into landslipped material. At Braes, 12 km south of Portree, a tombolo rising to *ca*. 7 m OD extends out to the granite islet of An Àird (Figure 13-150). Further south, at Rubha an Torra Mhòir on the north side of Loch Sligachan, the raised beach is particularly obvious (Figure 13-151; Figure 13-152); on the opposite side of the Narrows of Raasay, at Àird Ghiuthais on Raasay, is a similar raised beach (Figure 13-153). At the head of Loch Brittle, there is a rare example of sand dunes that most likely formed during and subsequent to the Main Postglacial Transgression. At Camas nan Geall on the south coast of Ardnamurchan, there is an example of an inclined raised beach (Figure 13-154).



Figure 13-150: Raised tombolo between Braes and An Àird on the north side of the entrance to Loch Sligachan, Skye. Across the Narrows of Raasay is the island of Raasay.

Beta version



Figure 13-151: The raised beach at Rubha an Torra Mhòir on the north side of the entrance to Loch Sligachan. View towards the north to the Trotternish Escarpment.



Figure 13-152: Raised beach deposits, Balmeanach Bay, Narrows of Raasay, Skye.

Peer review



Figure 13-153: Multiple raised beach levels indicated by terraces, northern end of Àird Ghiuthais, SW Raasay.



Figure 13-154: Inclined raised beach, Camas nan Geall, south Ardnamurchan. with Ben Hiant in distance.

Preview version

Other excellent example of raised beaches on Skye are at Camas Malag on the east side of Loch Slapin, Strath, and at Camasunary Bay, SE of the Cuillin (Figure 13-155; Figure 13-156; Figure 13-157; Figure 13-158).



Figure 13-155: Camas Malag on the east coast of Loch Slapin with its prominent raised beach. View towards the NW from the Kilbride – Suisnish track, Strath.



Figure 13-156: Detail of the raised beach at Camas Malag on the east coast of Loch Slapin. View towards the west, with the Blà Bheinn - Clach Glas - Garbh-bheinn ridge in the distance.

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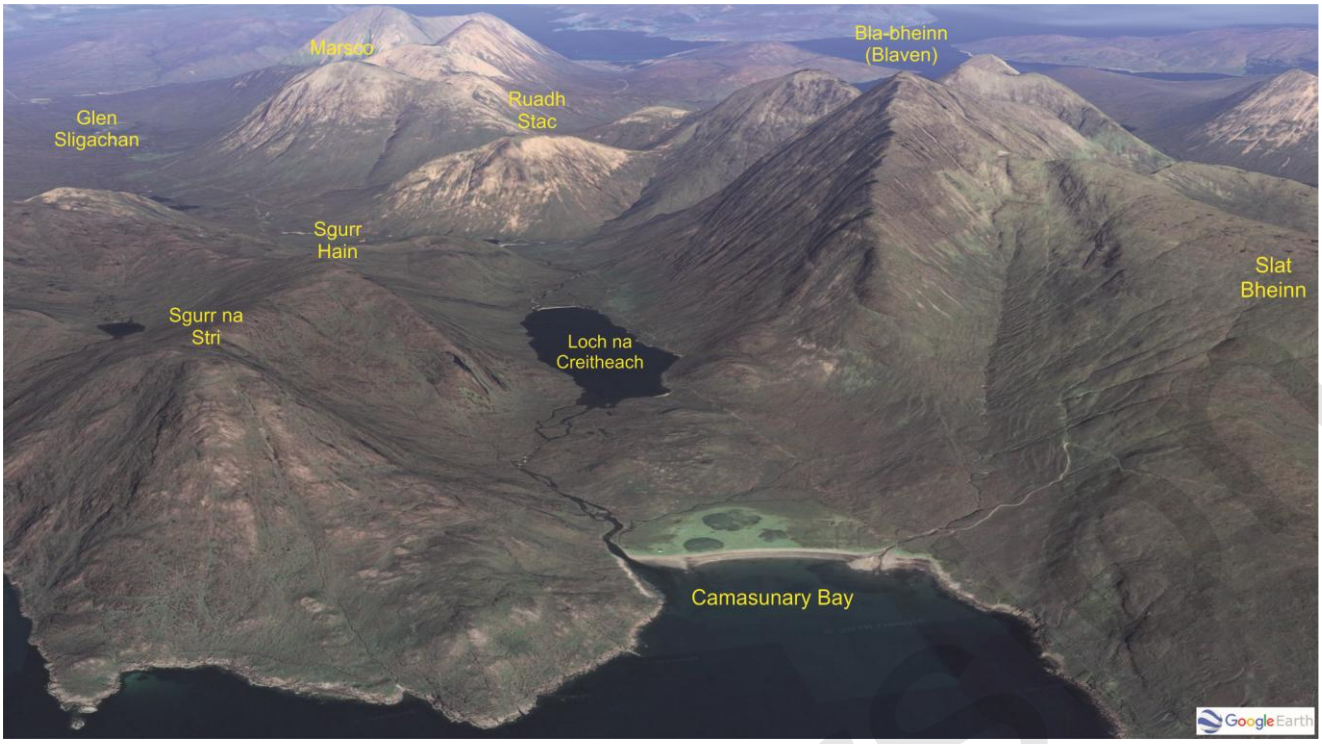


Figure 13-157: Oblique Google Earth© image of the glacial U-shaped valley of Glen Sligachan – Srath na Crèitheach, with a raised beach at its southern end in Camasunary Bay. View towards the north.



Figure 13-158: Raised beach at Camasunary Bay, SE of the Cuillin, viewed towards the west, with the main Cuillin ridge in the distance.

At Ardalanish Bay, SW Mull, the raised beach is 'punctured' by small hillocks, which would have been coastal islets when sea level was higher (Figure 13-159).



Figure 13-159: Raised beach at Ardalanish Bay on the south coast of the Ross of Mull, SW Mull. The isolated hillocks (high ground) would have been coastal islets at the time when sea level was higher.

Pockets of postglacial raised beach gravels, up to *ca*. 6 m OD, are present on most of the Small Isles. On Rum, a thin covering of raised beach sand and gravel at the head of Loch Scresort underlies the made ground at Kinloch Castle. Postglacial raised beaches also occur, for example at the foot of the Late-glacial raised beach deposits at Harris, Guirdil and Kilmory. On northern Eigg, near Talm, a postglacial raised beach is cut into landslip deposits, and is partially covered by later landslip debris, and to the south at the Bay of Laig, Holocene blown sand partly covers a postglacial raised beach.

Remnants of postglacial beaches are common on Mull, where they occur as gravel and sand beach terraces, sloping banks and spits, or as notches in morainic deposits, for example in the 'Loch Don Sand Moraine' west of Gorten. At the seaward end of Glen Forsa, an extensive spread of postglacial raised beach deposits at *ca*. 9.5 m OD underlies the airstrip and raised shingle ridges, and remnants of terraces up to 11.2 m OD occur around the head of Loch na Keal. More than one beach level may be present, as at Carsaig Bay (Figure 13-160; Figure 13-161). At Fishnish, a beach at *ca*. 12 m OD, marking the Main Postglacial Shoreline, is accompanied by less well-defined beaches at *ca*. 7 and 3.3 m OD. Raised beaches are sparsely represented on Ardnamurchan but are present at Kilchoan Bay where some are regarded as postglacial in age.



Figure 13-160: Multiple raised beach levels indicated by terraces, Carsaig Bay, SW Mull.

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Figure 13-161: Detail of multiple raised beach levels indicated by terraces, Carsaig Bay, SW Mull.

The (previously) rabbit-infested sands on Sanday (and Canna) are interpreted to be part of an extensive raised beach system, formed and reworked during Lateglacial high sea level(s) and modified and thickened by aeolian processes during the Holocene (Figure 13-162).



Figure 13-162: Rabbit-infested sands, Sanday, part of an extensive raised beach system. Rabbits for scale.

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Remnants of postglacial raised beach deposits occur at various localities around the coast of Arran (Figure 13-163) (Gemmell 1972). They are especially well developed where abundant detritus was available from the erosion of moraines; good examples occur at Brodick Bay and north of the mouth of the Sannox River. Postglacial shoreline deposits also occur on the Main Rock Platform. The beach deposits contain shell fragments similar to those of present-day beaches.



Figure 13-163: Stratified raised beach deposits, east of Kilpatrick Point, west Arran. Pole *ca*. 1 m long.

13.13 Landslips

On Skye, landslips occur at intervals all along the east-facing lava scarp from near the mouth of Loch Sligachan to the northern end of Trotternish (Figure 13-164; Figure 13-165; Figure 13-166; Figure 13-167; Figure 13-168; Figure 13-169; Figure 13-170; Figure 13-171; Figure 13-172; Figure 13-176; Figure 13-177; Figure 13-178; Figure 13-179; Figure 13-180; Figure 13-181; Figure 13-182; Figure 13-183; Figure 13-184; Figure 13-185; Figure 13-186; Figure 13-187; Figure 13-188; Figure 13-189). Figure 13-173 is the often-quoted, largely incorrect, landslip failure model of Anderson & Dunham (1966), whilst Figure 13-174 illustrates a more useful spectrum of failure mechanisms proposed by Ballantyne (1986).

In the spectacular examples at Quiraing (Figure 13-175; Figure 13-176; Figure 13-177; Figure 13-178; Figure 13-179; Figure 13-180; Figure 13-181), many of the slipped masses at lower elevations are ice-sculpted and may predate the Main Late Devensian Glaciation (Figure 13-1; Figure 13-2). However, the angular, unmodified outlines of those landslips closest to the present-day scarp, with their steep spires,

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cliffs and rock pinnacles, could not have survived ice action and must postdate the Main Late Devensian Glaciation.

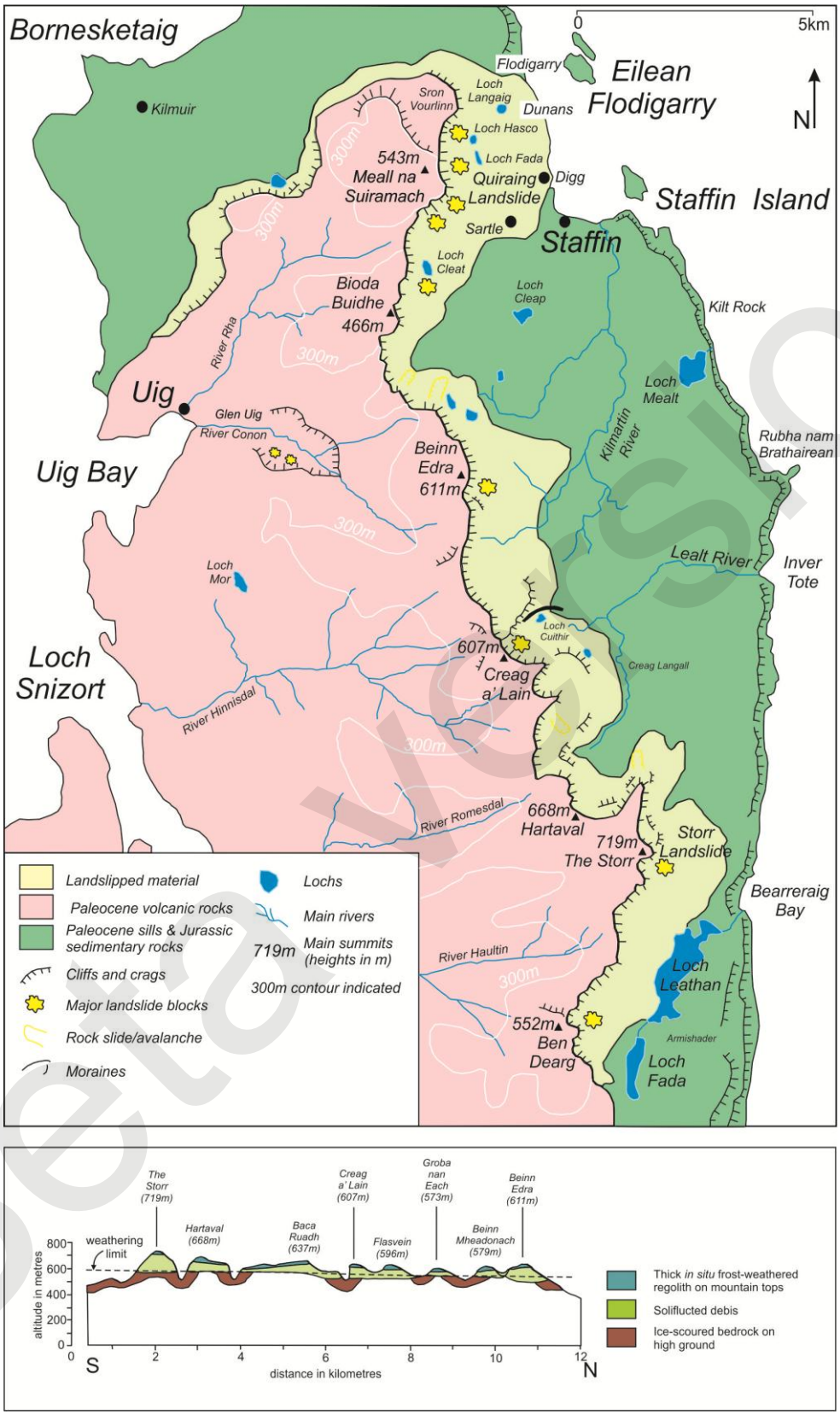


Figure 13-164: Simplified geological map depicting the extent of the landslips of the Trotternish Escarpment of northern Skye (after Ballantyne 2016).

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Figure 13-165: The Trotternish Escarpment, viewed towards the north from Loch Sligachan, Skye.



Figure 13-166: The Storr section of the Trotternish Escarpment landslip, with the prominent rock pillars of The Old Man of Storr (the largest, most obvious spire) and, beyond, The Needle (the small spire immediately to the left). View towards the north.

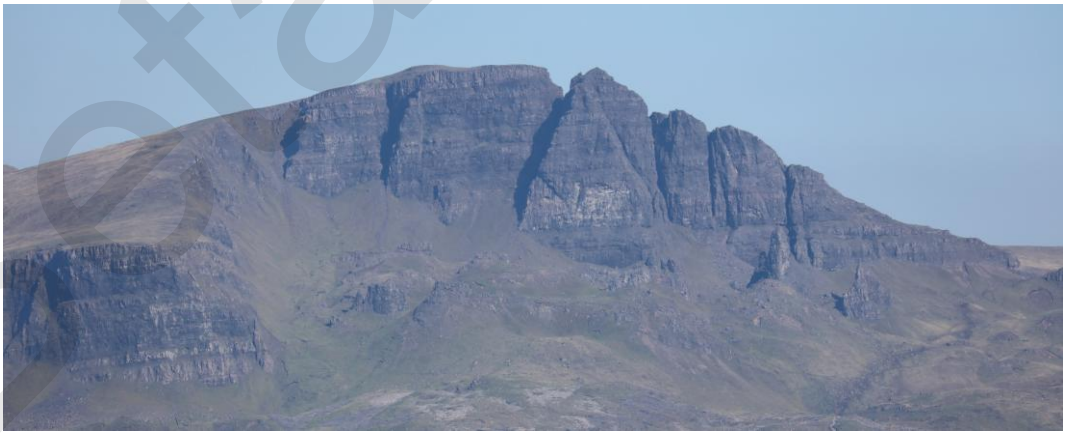


Figure 13-167: The Storr section of the Trotternish Escarpment landslip, with the prominent rock pillars (right-of-centre) of The Old Man of Storr (the largest, most obvious spire) and, to its right, The Needle, both below the skyline. The highest point on the escarpment is The Storr. View towards the NW from the Storr Lochs Dam, where the Bearreraig River exits Loch Leathan.

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Figure 13-168: The Storr section of the Trotternish Escarpment landslip, with the prominent rock pillars of The Old Man of Storr (the largest, most obvious spire) and, in line and nearer, The Needle. The highest point on the escarpment is The Storr. View is towards the south, towards the Storr Lochs.



Figure 13-169: Detail of The Storr section of the Trotternish Escarpment landslip, with the prominent rock pillars of The Old Man of Storr (the largest, most obvious spire) and, in line and nearer, The Needle. View is towards the south, towards the Storr Lochs.

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Figure 13-170: The Old Man of Storr, a rock pillar composed of Paleocene lavas, part of the landslip on the east side of The Storr escarpment. Person for scale.

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Figure 13-171: Views up (a) and down (b) of the Storr section of the Trotternish Escarpment landslip, with the prominent rock pillar of The Old Man of Storr (the largest, most obvious spire) and, in (a) to its right, The Needle. The highest point on the escarpment is The Storr. View in (a) towards the NW, and in (b) towards the east.

Preview version



Figure 13-172: Needle Rock, adjacent to The Old Man of Storr, Trotternish.

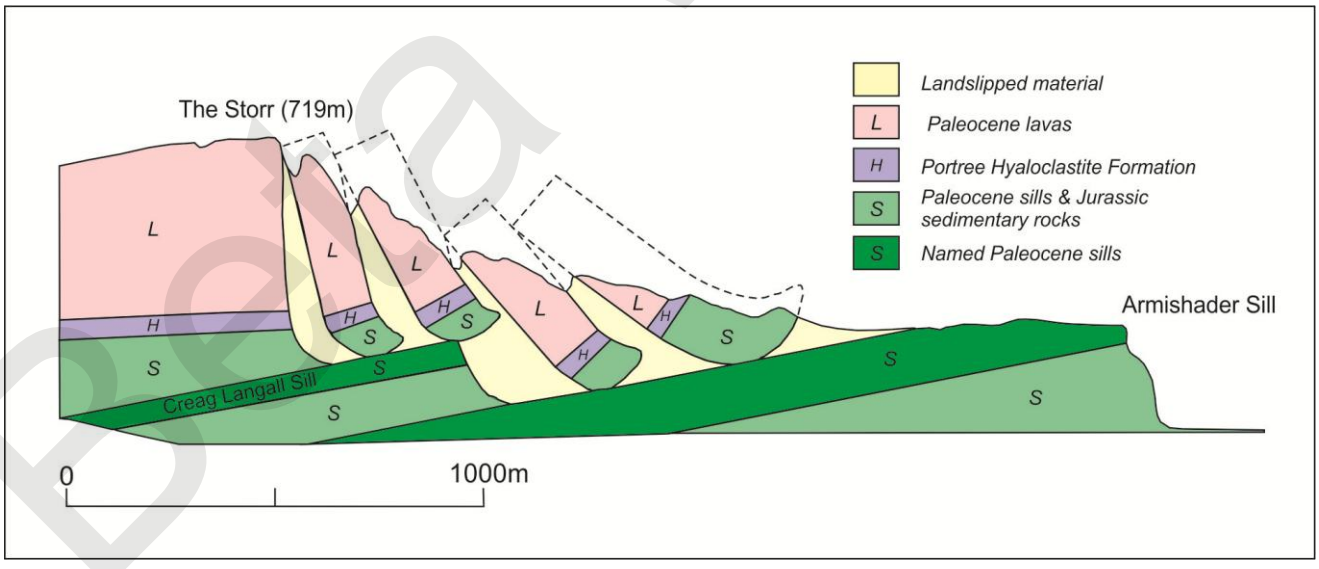


Figure 13-173: The simplistic, commonly quoted and largely incorrect, Anderson & Dunham model to explain the Storr Landslip (after Anderson & Dunham 1966).

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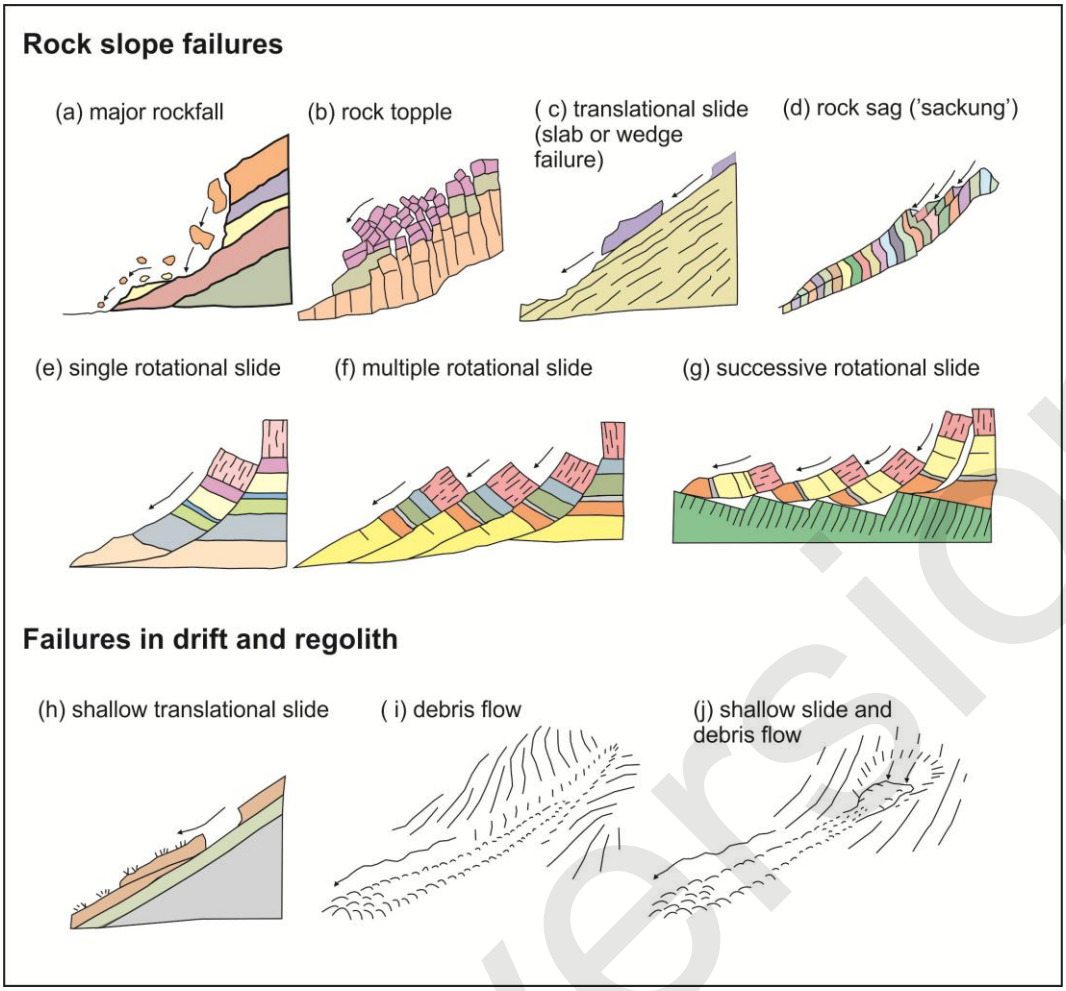


Figure 13-174: Principal types of slope failure in rock, drift and debris (after Ballantyne 1986)



Figure 13-175:Information panel at the Quiraing, Trotternish, Skye.

Review version



Figure 13-176: The Quiraing, a spectacular line of cliffs and associated landslipped blocks of Paleocene lavas at the northern end of the inland escarpment on Trotternish.

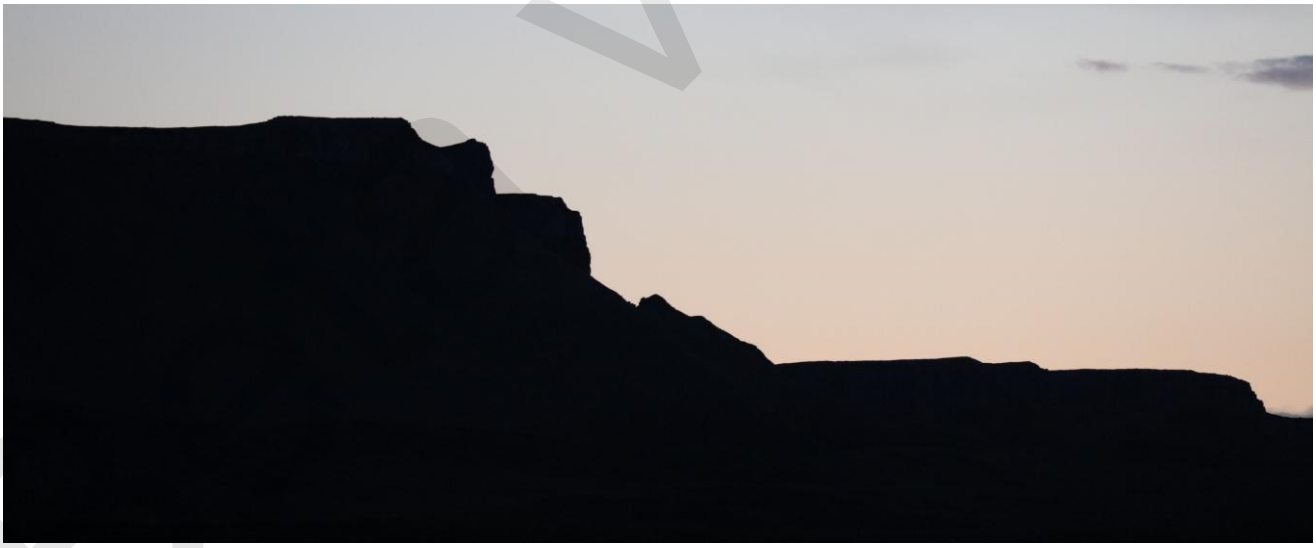


Figure 13-177: The northern end of the Quiraing Landslip in silhouette in profile at dusk.

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Figure 13-178: The Needle, a spire of landslipped Paleocene lavas, at the Quiraing on the Trotternish Escarpment. View is towards the NW.



Figure 13-179: The Table, a remarkably flat-surfaced block of lavas at the Quiraing on the Trotternish Escarpment. Sheep at the far end for scale. View is towards the south.

Preview version



Figure 13-180: View from Sròn Vourlinn on the Trotternish Escarpment, towards the south. The small loch in the distance (top right) is Loch Fada. These lochs are common along the base of the escarpment and have developed due to the impervious nature of the detritus that has formed by the landslip events and the presence of moraines.



Figure 13-181: View from the Trotternish Escarpment from north of the Quiraing, NE towards Flodigarry, with Loch Hasco (nearest) and Loch Langaig (farthest). These lochs are common along the base of the escarpment and have developed due to the impervious nature of the detritus that has formed by the landslip events and the presence of moraines.

Preliminary version



Figure 13-182: The Beinn Edra Landslip, west of Marishader, Trotternish.

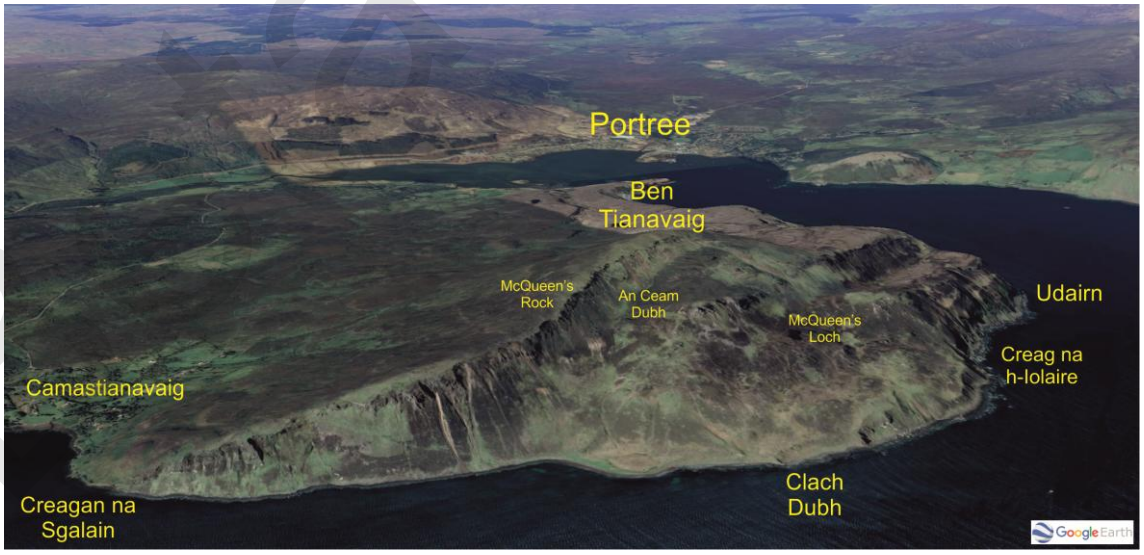


Figure 13-183: Oblique Google Earth© image of the Ben Tianavaig Landslip, south of Portree. View towards the NW.

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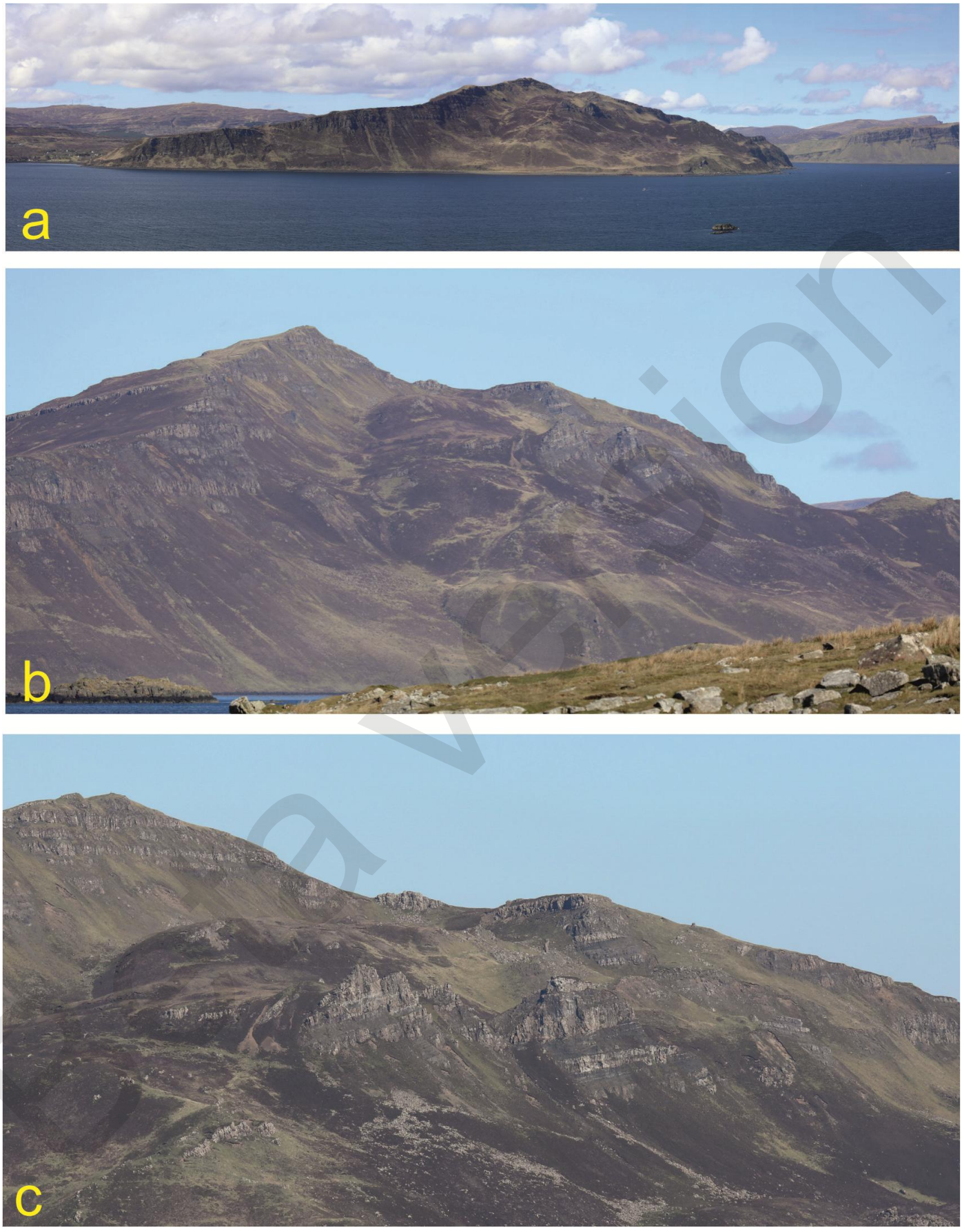


Figure 13-184: The Ben Tianavaig Landslip, south of Portree, viewed towards NNW from south Raasay.

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Figure 13-185: Details of the chaotic nature of the Ben Tianavaig Landslip: (a) towards the NE; and, (b) towards the SE, with Raasay in the distance.

Some of the landslips remain active, as at Flodigarry, in north Trotternish (Figure 13-186; Figure 13-187; Figure 13-188; Figure 13-189).



Figure 13-186: Landslipped material east of the Trotternish Escarpment at Flodigarry. There is no simple logic to the topography, as it comprises rotated and toppled blocks of lava in a totally random manner. Note road sign warning.



Figure 13-187: Landslipped material on the coast at Dunans, south of Flodigarry. The material comprises rotated and toppled fragments of lava is a totally random manner. Note abandoned building and disrupted line of fence.

Draft version



Figure 13-188: Road damage at Flodigarry. Repairs are made on an almost annual basis due to ongoing minor movements within the landslipped material as it migrates eastwards towards the coast.



Figure 13-189: Road sign warning at Flodigarry.

The Glen Uig Landslides, east of Uig in Trotternish, involves the same key components as elsewhere on Trotternish, comprising very poorly exposed basaltic lavas with laterite tops overlying (largely obscured) Upper Jurassic shales of the Staffin Shale Formation (Figure 13-190; Figure 13-191). In this instance, the landslips are located on the dip slope of the escarpment. The largest and most obvious of the three named landslips is the so-called Fairy Glen Landslip. Much of the movement involved lateral movement and minor tilting of discrete, intact blocks, the most obvious of which is Castle Ewan. Rotational displacement of blocks and tilting has occurred but is localised. The other two landslides, at Peinchonnich and at Glen Conon, to the north of Fairy Glen, are also dominated by detached blocks that have undergone lateral movement, with only a minor amount of tilting by rotation.

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Figure 13-190: Google Earth© images and field photographs of the Fairy Glen Landslip. The post prominent block, Castle Ewan, comprises relatively well exposed basaltic lavas.

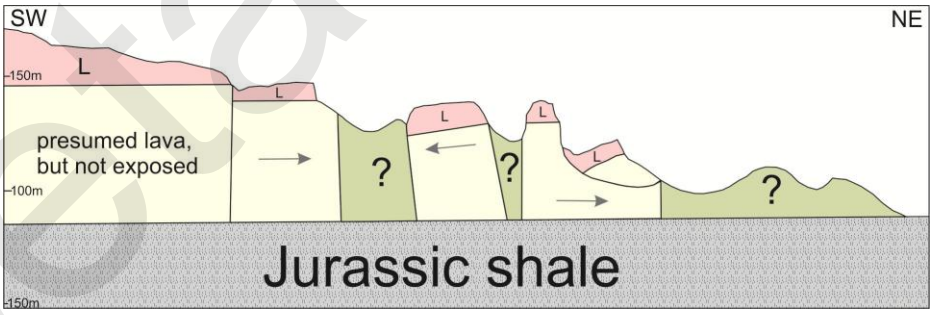


Figure 13-191: Conceptual cross-section of the Fairy Glen Landslip, illustrating the nature of block movement. Much of the bedrock is obscured by weathered material and unclassified 'drift'. (after Ballantyne & Lowe 2016).

In west-central Skye there are a few landslips, for example at Biod an Athair, SW of Dunvegan Head (Figure 13-192), and at Waterstein Head, Duirinish (Figure 13-193). On the west side of Strathaird at Càrn Mòr there is another obvious landslip (Figure 13-194). In central Skye, there are a few smaller, less spectacular landslips, for example on the NE side of Glas Bheinn Mhór, where the landslip is superimposed on deposits that might be attributed to the Loch Lomond Stadial.

Beta version



Figure 13-192: Landslip, Biod an Athair, SW of Dunvegan Head, Duirinish, NW Skye.



Figure 13-193: The Waterstein Head landslip, viewed towards the east from Neist Point (Rubha na h-Eist): the Neist Sill forms the obvious jointed exposure in the middle distance, the inclined lavas in the distance belong to the Ramasaig Group, the landslip disrupts the lavas and gives rise to the brown and white detritus on the coastline below the lavas.

Preview version

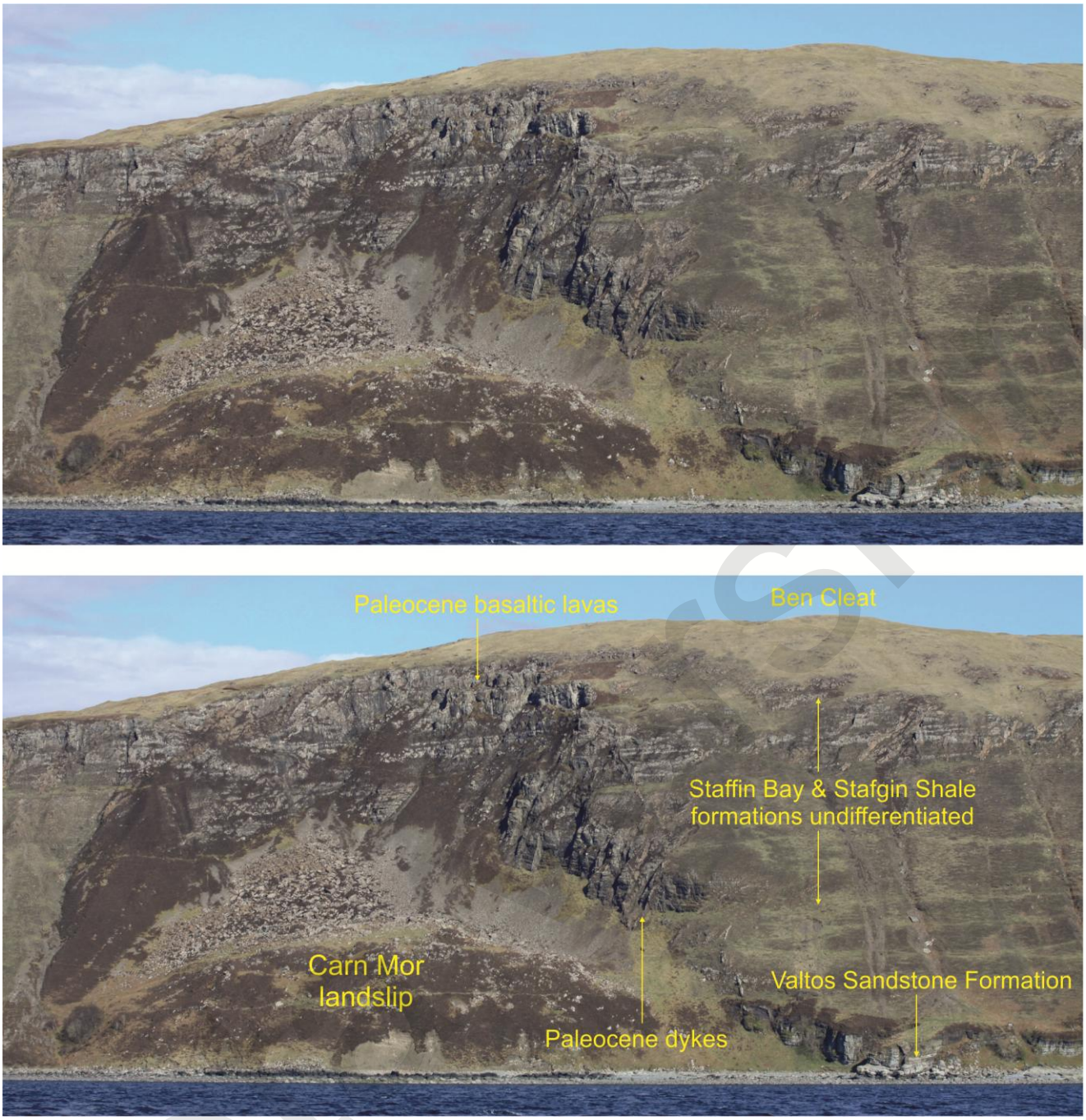


Figure 13-194: The Càrn Mòr Landslip, composed of basaltic lavas, on the west coast of Strathaird.

Large landslips and rock falls occur in east and SE Raasay (Figure 13-195): the Hallaig and the Beinn na Leac landslips.

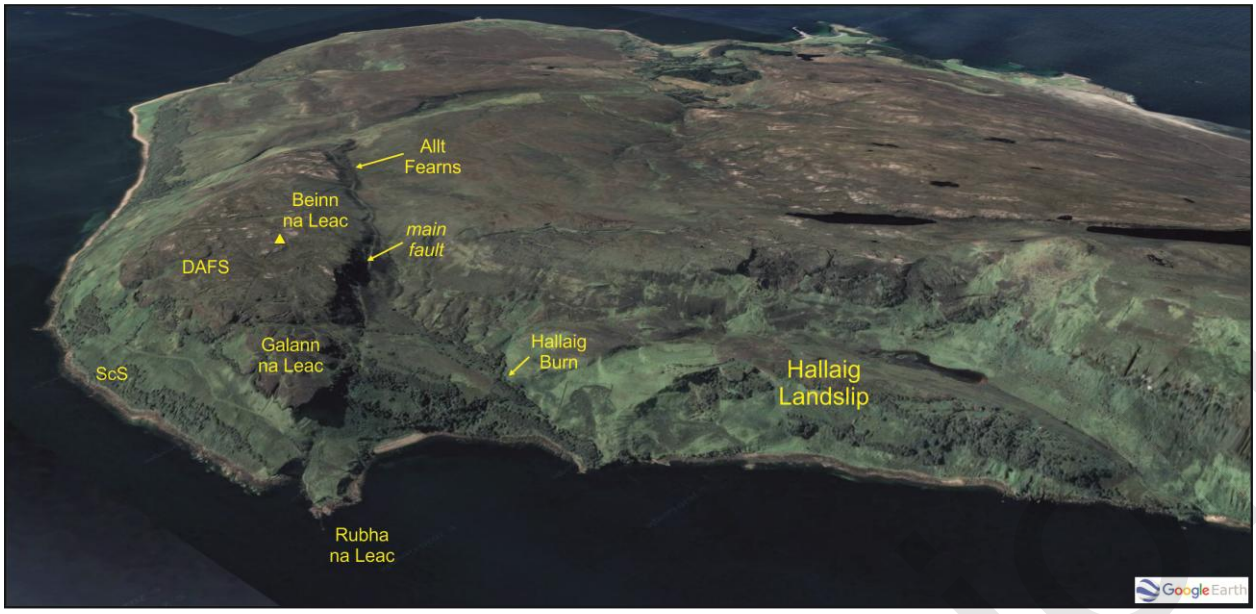


Figure 13-195: Oblique Google Earth© image of the Hallaig and Beinn na Leac landslips in SE Raasay. ScS: Scalpay Sandstone Formation; DAFS: Druim an Fhuarain Sandstone Member.

A major fall within the Hallaig Landslip (Figure 13-196; Figure 13-197; Figure 13-198; Figure 13-199) was reported at Hallaig in 1934. Fissuring of the thick sequence of Middle Jurassic Bearerraig Sandstone Formation strata can be attributed to, or has been accentuated by, landslipping.



Figure 13-196: The Hallaig Landslip in SE Raasay. View towards the SE from Brochel on the east coast of the island.

Beta version



Figure 13-197: The Hallaig Landslip (left of centre), with multiple internal bench-like scars, and (in the distance) the northern part of the Beinn na Leac Landslip in SE Raasay. View towards the SE from the summit of Dùn Caan.



Figure 13-198: Detail of the Hallaig Landslip, with multiple internal bench-like scars, and (in the distance, top right) the northern part of the Beinn na Leac Landslip in SE Raasay. View towards the SE from the summit of Dùn Caan.

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Figure 13-199: Detail of the Hallaig Landslip, with active fractures separating slipped and rotated blocks of Bearreraig Sandstone Formation strata. View towards the north at Hallaig.

The Beinn na Leac Landslip at the SE end of Raasay is also still active, with one large scar/fault at the back of the main block, against Lower Jurassic Pabay Formation strata, and several very deep fissures within the block (Figure 13-200; Figure 13-201; Figure 13-202; Figure 13-203). The landslip collapsed towards the SE, into the glacially scoured trough off the Raasay coast. Initiation of the landslip was most likely due to the removal of material when the trough was formed. The block did not appreciably rotate and remained essentially coherent, albeit with significant fissures. In the SW part of the landslipped block, two branch faults are recognised. Relative timing of movement of these branches and landslip formation can be determined from their relationship with Devensian tills. The branch to the SW is partially blanketed by undisturbed Devensian till (and Holocene peat), indicating movement only prior to till deposition, possibly due to the presence of offshore glacial deposits blocking any subsequent (later) movements. The branch to the NE is not covered by till and most likely had movements in post-Devensian times (during the Holocene; from 11.7 ka, onwards), as also suggested by disrupted deposits of scree.

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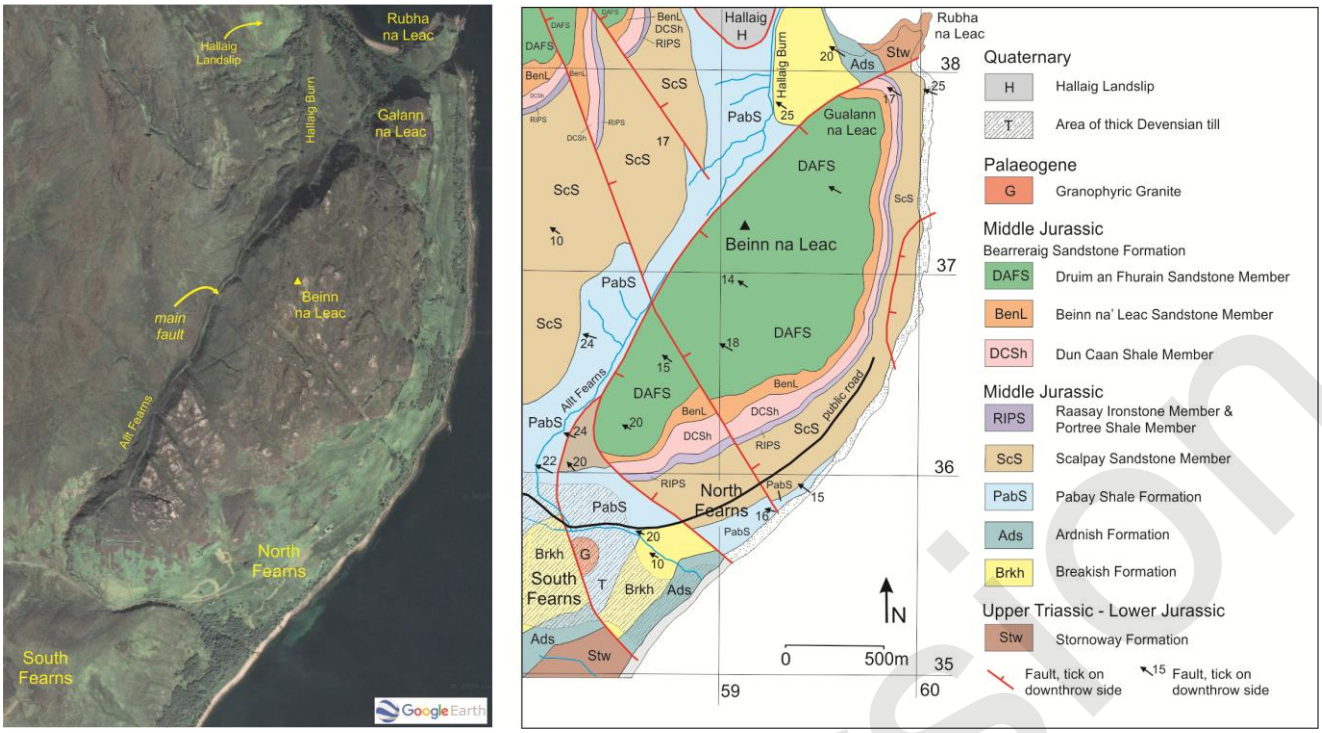


Figure 13-200: The Beinn na Leac Landslip in SE Raasay (based on BGS (2006a) and Morton (2014)). This is the Hallaig Landslip of Smith *et al*. (2009).



Figure 13-201: Fissures within Bearreraig Sandstone Formation strata within the Beinn na Leac landslipped block, SW of Beinn na Leac.

Preliminary version



Figure 13-202: A deep fissure within Bearreraig Sandstone Formation strata within the Beinn na Leac landslipped block, SW of Beinn na Leac.



Figure 13-203: Detached rock pillar at Gualann na Leac, part of the Beinn na Leac Landslip, SE Raasay.

The Screapadal Landslip comprises the inland crags of Druim an Aonaich in east central Raasay, with several minor landslipped blocks and insipient failures (Figure 13-204; Figure 13-205; Figure 13-206)



Figure 13-204: Insipient failures within the Druim an Fhuarain Sandstone Member between Creag na Bruaich and Druim an Aonaich on the east coast of Raasay. View towards the south from Brochel.

Comparisons of the variable nature of landslips can be made by contrasting the Hallaig and Screapadal landslips (Figure 13-205).

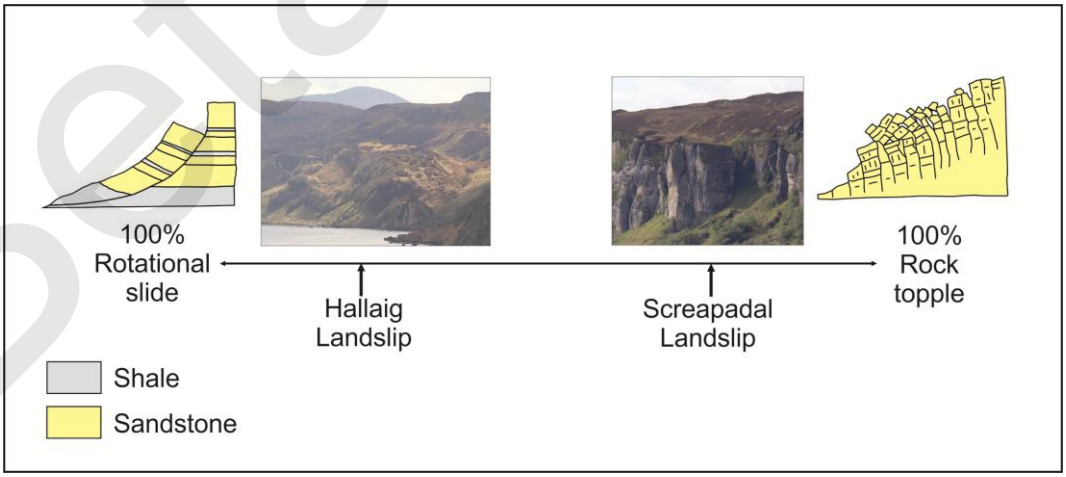


Figure 13-205: Schematic comparison of the Hallaig and Screapadal landslips.

Beta version



Figure 13-206: Fallen block, part of the Screapadal Landslip at Eaglais Briege, South Screapadal, east Raasay.

Small landslips are present along the granite cliffs of SW Rum, but the most spectacular examples in the Small Isles occur around the edges of the lava escarpments in northern Eigg. There, a major postglacial landslip on the coast at Talm is likely to be still active, but west of the Bay of Laig, postglacial beach deposits are banked against an older rotational slip (Figure 13-207; Figure 13-208; Figure 13-209). On the NE coast of Eigg, both ancient scree-covered landslips and more recent landslips are identified, and there is abundant evidence of recent rockfalls, usually involving the Middle Jurassic Valtos Sandstone Formation and the overlying Paleocene lavas.



Figure 13-207: Oblique Google Earth© image of NW Eigg, indicating the location of the Cleadale landslip. View towards east.

Beta version



Figure 13-208: The Sgòrr an Fharaidh ridge, NW Eigg and, below, the Cleadale Landslip.

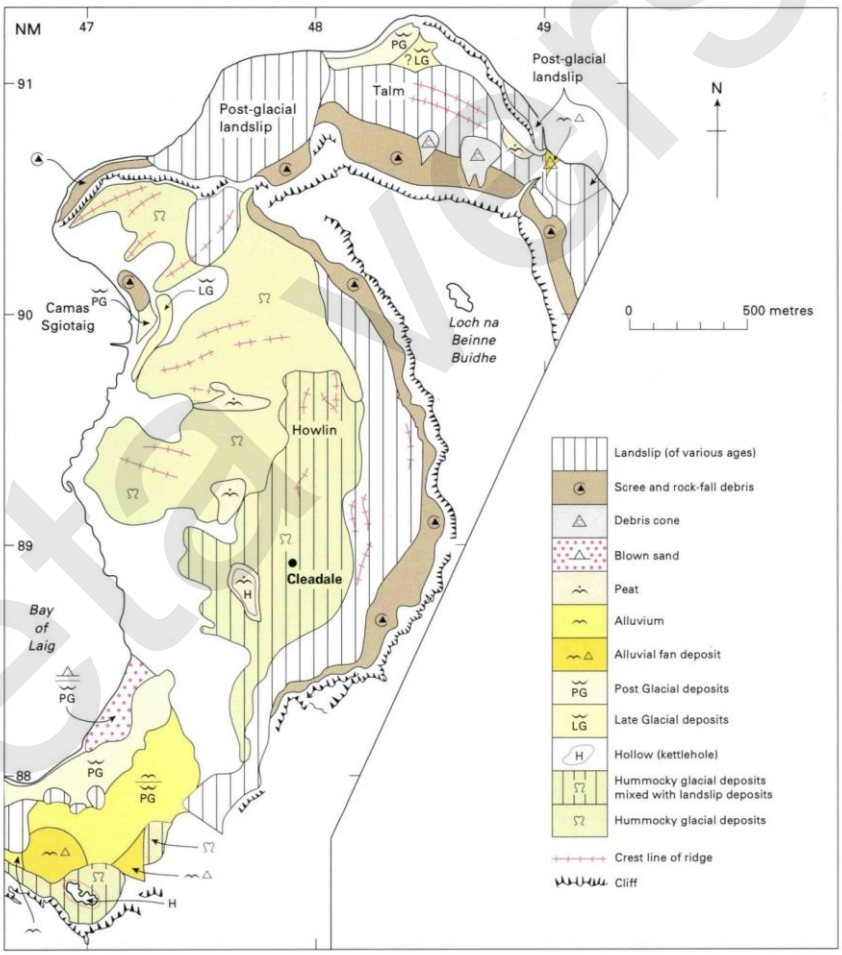


Figure 13-209: Pleistocene and Recent deposits and features, NW Eigg. In the south of the island, at Grulin Cottage, numerous scattered large blocks of columnar pitchstone are part of a rockfall from the south face of An Sgùrr (after Emeleus 1997).

Beta version



Figure 13-210: The Talm landslips, north Eigg.

Compass Hill, at the east end of Canna, has partially landslipped, with randomly oriented blocks of lava and volcaniclastic sedimentary rock along the base of the coastal cliffs (Figure 13-211; Figure 13-212).

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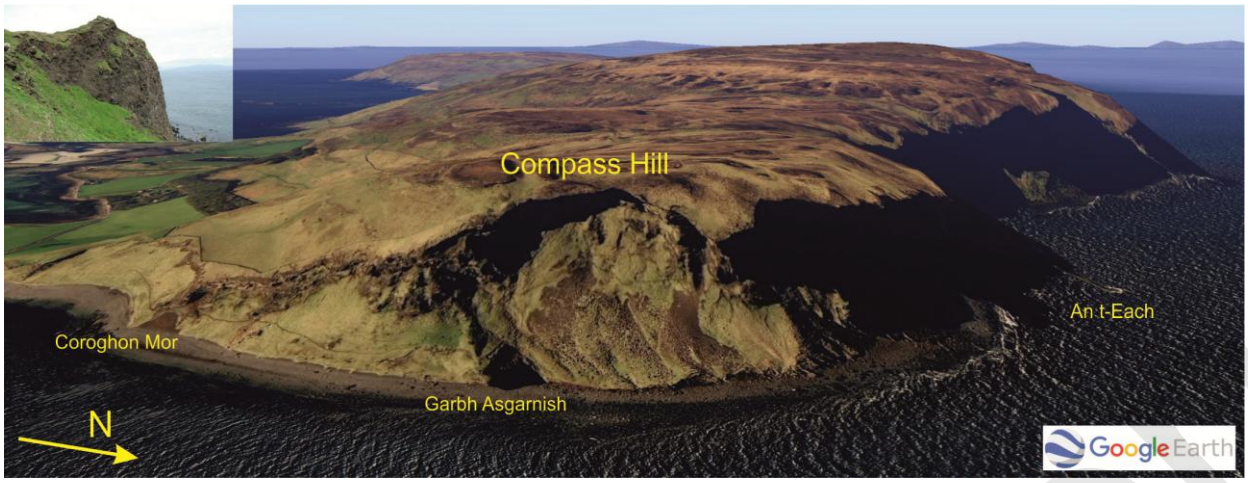


Figure 13-211: Oblique Google Earth© image of the Compass Hill Landslip at the east end of Canna. View towards the west.



Figure 13-212: Landslipped block at the foot of the Compass Hill Landslip at the east end of Canna.

Browser version

On Mull, landslips of both pre-Late Devensian and postglacial or Late-glacial age are recognised at Gribun and Clachandu (Figure 13-213; Figure 13-214), and modern examples occur in The Wilderness on the Ardmeanach peninsula.



Figure 13-213: Landslip, Gribun, north Ardmeanach, west-central Mull.



Figure 13-214: Landslipped block of Paleocene lavas at Clachandhu on the south side of Loch na Keal, west Mull.

Landslips are prominent on the SW side of Beinn Iodain, south of Loch Teacuis, and south of Loch Arienas, in Morvern, where outliers of Paleocene lavas overlie a thin Mesozoic succession (Figure 13-215).

Beta version



Figure 13-215: Landslipped blocks on the SW side of the Beinn Iodain lava outlier, Morvern.

Rockfalls are common due to the instability of many of the volcanic rocks, for example the cliffs NE of Maclean's Nose on the south coast of Ardnamurchan (Figure 13-216).



Figure 13-216: Rockfall, NE of Maclean's Nose, south Ardnamurchan.

The well-known Fallen Rocks on Arran are the site of landslips involving Old Red Sandstone conglomerates. Further north, at An Scriadan east of the Cock of Arran, large blocks of Permian sandstone

collapsed less than 300 years ago, with a noise that was heard over a wide area (Figure 13-217; Figure 13-218).



Figure 13-217: The Fallen Rocks, NE Arran.



Figure 13-218: The Fallen Rocks, NE Arran.

13.14 Talus and other upland features

The present-day environment on the mountain tops of the Inner Hebrides and Arran is dominated by copious rain and high winds: not constant, but frequent. The meagre vegetation is removed by the wind and by grazing animals, laying bare to erosion the silt and fine sand in the poorly developed soil. This leaves

relatively coarse lag deposits and enables the formation of low, turf-banked terracettes which are very noticeable on the higher hills.

Talus (large fragments) and scree (small fragments) deposits, commonly comprising unmodified rockfall accumulations, are well represented in the mountainous areas and along sea cliffs. It is not difficult to distinguish older deposits, stabilised by soil and vegetation, from younger, mobile accumulations, for example in the Cuillin, around Loch Coruisk (Figure 13-219), in the Red Hills of Strath, Skye (Figure 13-220), and banked up against the microgranite cliffs of SW Rum.

Fine active examples of talus and scree are found within the Cuillin of Skye, where the coarse mobile debris forms 'stone chutes', the best known of which is the Great Stone Chute at the head of Coire Làgan (Figure 13-221; Figure 13-222; Figure 13-223; Figure 13-224). Elsewhere on Skye, the pale ground of the Paleocene rhyolitic volcanic rocks on the north side of the Cuillin (Figure 13-225), the Coire Uaigneich Granite on the east side of Blà Bheinn (Figure 13-227), and the Red Hills (in general) arises in large part from their mantles of rock debris, of which the coarse bouldery talus and scree on Glamaig and Beinn na Caillich are of note (Figure 13-228; Figure 13-229).

The talus below the vertical cliffs of the two outliers of the Talisker Formation lava in Minginish, west-central Skye (Chapter 6), contains obvious hexagonal columns (Figure 13-226)

Talus and scree accumulations are common in the mountains and on the coasts of Rum (Figure 13-230; Figure 13-231), Raasay (Figure 13-232), Mull (Figure 13-233) and Arran (Figure 13-234; Figure 13-235).

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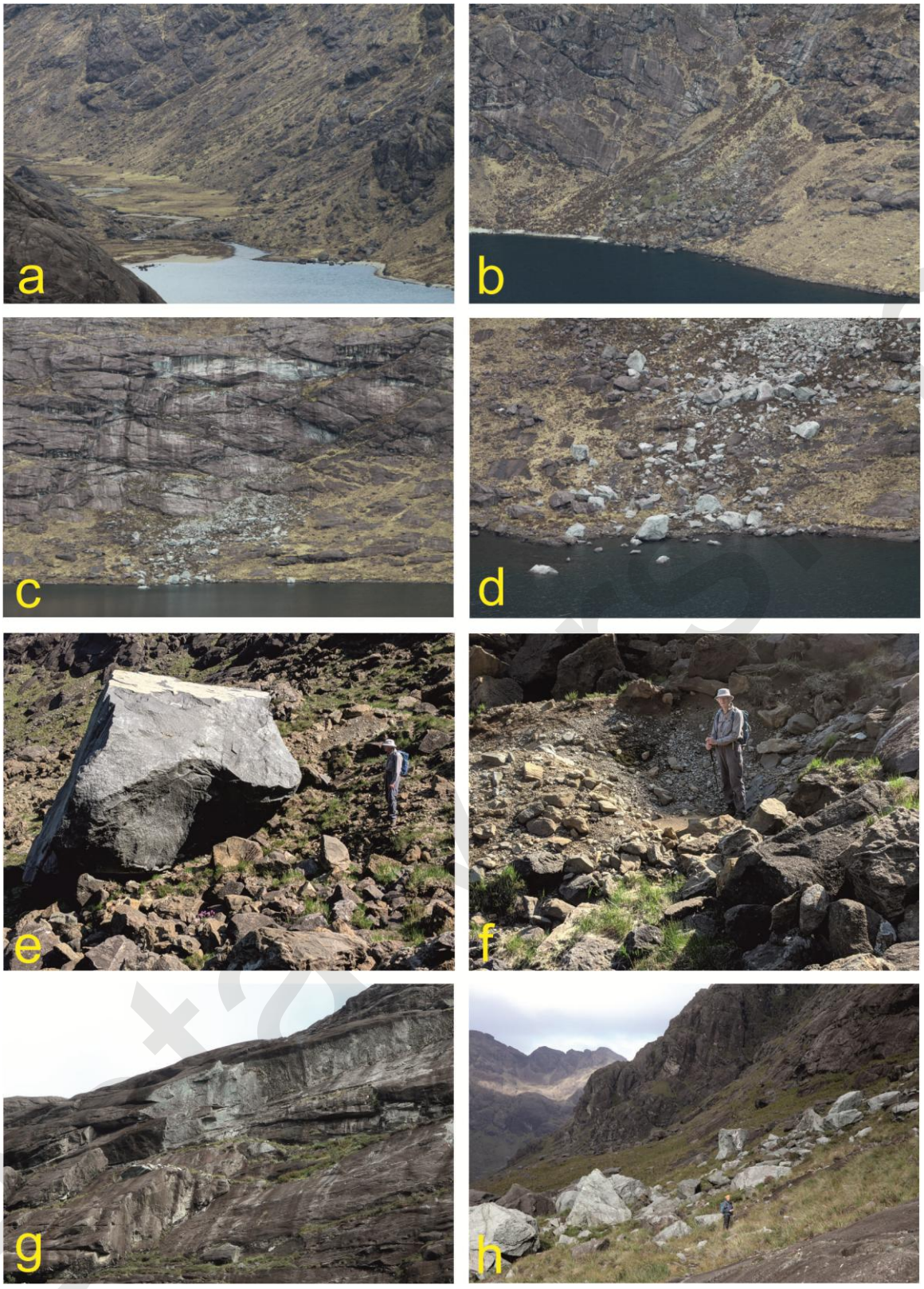


Figure 13-219: (a & b) Partially vegetated old talus deposits on the north side of Loch Coruisk at its NW end. Such accumulations are relatively common where minor intrusions invade 'country-rock' gabbro (and similar coarse-grained basic rocks) on glacially produced (now steep) faces; (c & d) on the NE side of Loch Coruisk (at its southern end) are more recent taluses, one of which formed in the early 1980s; (e & f) a recent rockfall and impact depression in An Garbh-choire (Iain Allison for scale) and, (g & h) a recent rockfall on the NE side of Loch Coruisk, on the SW side of Druim nan Rahm.



Figure 13-220: Vegetated talus, western end of Coire Odhar, below Beinn Dearg Bheag, Strath, Skye.



Figure 13-221: The Great Stone Chute in Coire Làgan between Sgùrr Alasdair (right-hand-side) and Sgùrr Thearlaich (left-hand-side), Cuillin, Skye. This huge scree is due to efficient freeze-thaw action on steeply inclined minor intrusions within the Cuillin Intrusive Centre. View towards ENE.

Preview

F

Figure 13-222: The Great Stone Chute in Coire Làgan between Sgùrr Alasdair (right-hand-side) and Sgùrr Thearlaich (left-hand-side), Cuillin, Skye. This huge scree is due to efficient freeze-thaw action on steeply inclined minor intrusions within the Cuillin Intrusive Centre. View towards ENE.



Figure 13-223: The Great Stone Chute in Coire Làgan between Sgùrr Alasdair (right-hand-side) and Sgùrr Thearlaich (left-hand-side), Cuillin, Skye. This huge scree is due to efficient freeze-thaw action on steeply inclined minor intrusions within the Cuillin Intrusive Centre. View towards ENE.



Figure 13-224: The reverse side of the top of the Great Stone Chute, as seen from Bealach a' Garbh-choire.



Figure 13-225: Scree blanketing parts of the west side of Meall Odhar, northern Cuillin, Skye. The scree covered summit of the Red Hill, Glamaig, is in the distance (top-right).

Beta version



Figure 13-226: Talus formed by the collapse of columnar-jointed basalt (lava), south side of Preshal Beg, Minginish, with (intact) columnar-faceted blocks.



Figure 13-227: Stone chute on the east side of Blà Bheinn, formed by efficient freeze-thaw action on the Paleocene Coire Uaigneich Granite. View towards the west.



Figure 13-228: Granite scree mantling the west side of Glamaig, Glen Sligachan, Skye.



Figure 13-229: Granite scree mantling the east side of Beinn na Caillich, Strath, Skye.

Preview



Figure 13-230: Orange-brown scree of Torridonian Supergroup strata below Bloodstone Hill, NW Rum.



Figure 13-231: Scree cones along the NW coast of Rum, formed of fragments of the Paleocene Western Granite.



Figure 13-232: Talus of Paleocene granite on the west side of Loch na Meilich, Raasay.



Figure 13-233: Scree on the SW side of Ben More (left) and A'Chioch (right), central Mull.

Draft version



Figure 13-234: Boulder talus, Creag Ghlas Laggan, Glen Chalmadale, SW Arran.



Figure 13-235: Scree / mud slide, An Scriodan, north Arran.

13.15 Coastal deposits and features

Boulders and shingle make up a large proportion of the present-day coastal beach deposits, for example on the shoreface at the base of the lava cliffs of Skye, Canna, Mull, Rum and Ailsa Craig (Figure 13-236; Figure 13-237; Figure 13-238; Figure 13-239; Figure 13-240; Figure 13-241; Figure 13-242; Figure 13-243). Elsewhere, sand is dominant and is commonly dark due to a significant proportion of basaltic detritus (Figure 13-244).



Figure 13-236: Sea cave above a boulder- and cobble-dominated storm beach, Oronsay, Loch Bracadale, Skye.

Beta version



Figure 13-237: Flotsam overlying talus at top of storm beach, west of Rubha Nic Eamoin, south Canna.



Figure 13-238: Spar cave at back of a geo/gio formed by differential erosion of a Paleocene dyke relative to a tough, resistant-to-erosion sandstone (Bearreraig Sandstone Formation), Glasnakille, Strathaird, Skye.



Figure 13-239: Detail of the entry to Spar Cave, with large stalactites formed from carbonate dissolved from the Bearreraig Sandstone Formation strata, and with remnants of a wall, possibly used to control entry to fee-paying 'customers' in the 19th Century.



Figure 13-240: Talus cone and boulder beach, Laggan, SE Mull. [Photographs courtesy of Jim Morrison]



Figure 13-241: Boulder beach formed from reworked talus from the cliffs of NW Ailsa Craig, Firth of Clyde.

Public Version

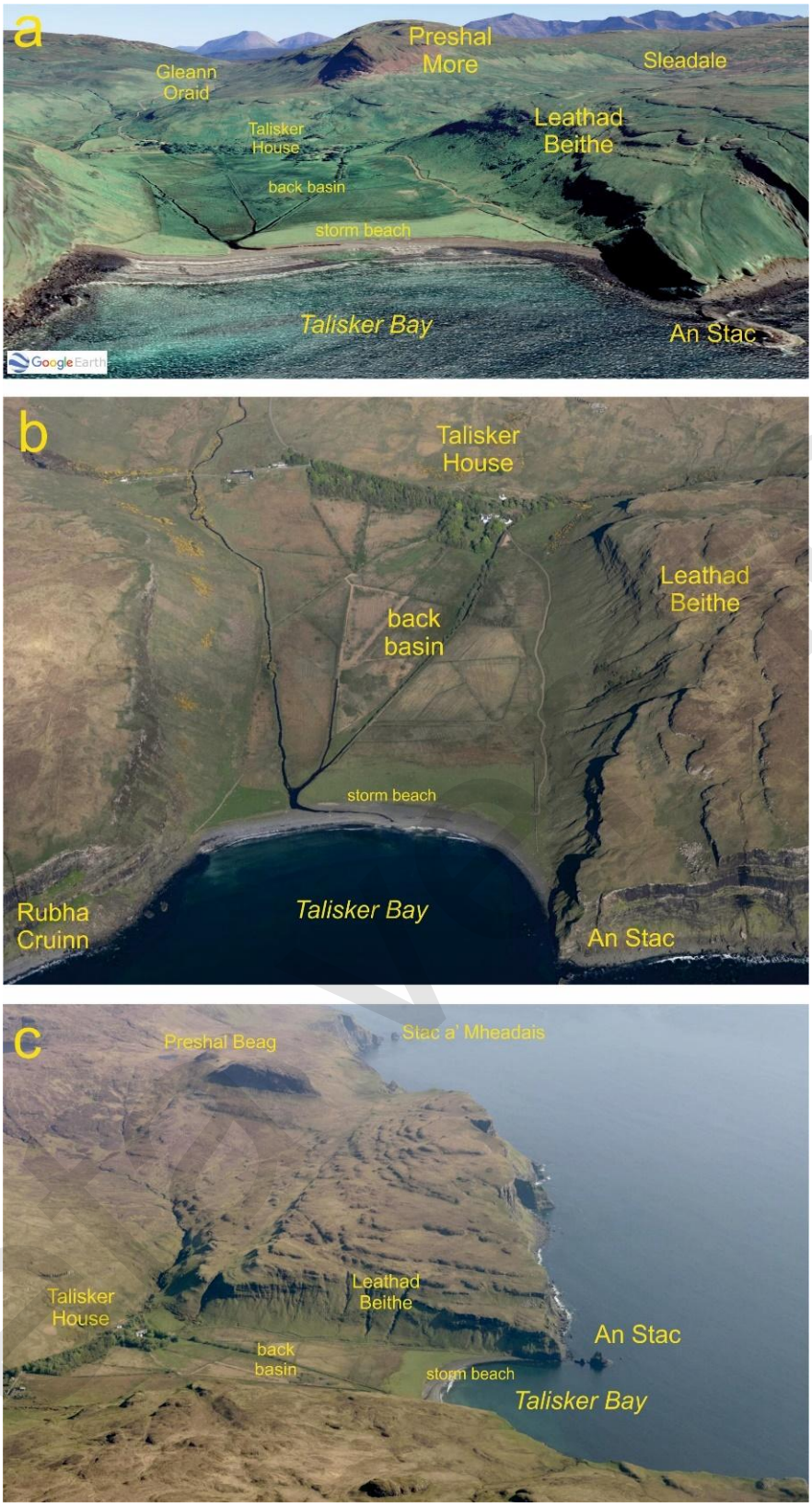


Figure 13-242: Oblique Google Earth© image and field views of Talisker Bay on the west side of Minginish, Skye, with its present-day beach and associated storm beach, behind which is a basin that is subjected to occasional inundation of the sea during exceptional tides and storm conditions. It has been recorded that that the sea has reached Talisker House, which is located *ca.* 1 km inland, although at an altitude of less than 10 m OD. (a): view towards the east with the valley of Gleann Oraid and the lava inselberg of Preshal More (320 m OD); and, (c) towards the SE.

Be



Figure 13-243: Sand beach and boulder storm beach, Talisker Bay, west-central Skye.





Figure 13-244: Dark basaltic sand beach and raised beach (far right, with campsite), Loch Brittle, west-central Skye.

Beta version

Sandy beaches are commonly made of material washed out of glacial deposits, as at Brodick Bay, Arran, and sandy detritus that has been derived from the weathering of nearby bedrock comprises other beaches, for example, Torridonian sandstone at Kilmory on Rum, New Red Sandstone at Kildonnan and Blackwaterfoot on Arran, and Middle Jurassic Valtos Sandstone at the Bay of Laig, Eigg. At Camas Sgiotaig, in the Bay of Laig, the 'Singing Sands' emit shrill squeaks when the dry sand is crushed underfoot (Figure 13-245).



Figure 13-245: The 'singing sands' of Camas Sgiotaig, west Eigg.

Beaches formed largely of shelly debris also occur, for example, at Calgary Bay (Figure 13-246; Figure 13-247), at Port Langamull in NW Mull, near Canna Harbour, and at Gaillinach on Muck.



Figure 13-246: Calgary Bay, NW Mull.

Beta version



Figure 13-247: Shelly sands at Calgary Bay, NW Mull.

The beaches on the west side of Iona contain rounded pebbles of brightly coloured gneiss and amphibolite derived from the Archaean basement Lewisian Gneiss Complex (Chapter 2), which forms much of the island. At the back of the beach are deposits of (Holocene) windblown shell sand, covered in grass (Figure 13-248; Figure 13-249; Figure 13-250), the so-called *machair*.



Figure 13-248: Raised beach, Camas Cùil an t-Saimh, west Iona.

Beta version



Figure 13-249: Beach, Camas Cùil an t-Saimh, west Iona.



Figure 13-250: Machair, west coast of Iona.

At a number of localities there are gleaming white beaches composed of fragments of the calcareous algae *Lithothamnion calcareum*. On Skye, examples of these so-called 'coral sands' are found north of Rubha na Gairbe on the east shore of Loch Dunvegan (Figure 13-251; Figure 13-252; Figure 13-253) and north of Ord in Sleat (Figure 13-254). Unlike most seaweed, it grows a hard outer (exo-) skeleton (thallus) composed of calcium carbonate and tends to form where there are significant currents. It grows unattached to the seabed, forming balls that roll around due to tidal currents. Colour is lost when exposed to the bleaching effect of direct sunlight and has the effect of causing the shallow water near the beach to take on a pale blue hue.

Beta version



Figure 13-251: 'Coral Sands', Claigan Coral Beach, Rubha na Gairbe, located on the east side of Loch Dunvegan between Waternish and Duirinish.



Figure 13-252: 'Coral Sands', Claigan Coral Beach, Rubha na Gairbe, located on the east side of Loch Dunvegan between Waternish and Duirinish, with tombolo to Lampay (island). In the far distance (left) is Healabhal Mhòr (Macleod's Table North).

Beta version



Figure 13-253: Detail of the Claigan 'coral sands' - fragments of carbonate exoskeletons of coralline seaweed. Coin *ca.* 20 mm across.



Figure 13-254: 'Coral sands' on Eilean Gaineamhach an Arda, NE of Ord, Sleat.

At Duntulm, in northern Skye, olivine from the weathering of nearby dolerite sills is a prominent constituent of the beach sand.

Tombolos are uncommon, with good examples being to the island of Lampay in Loch Dunvegan, Skye (Figure 13-252; see above), to Oronsay in Loch Bracadale, Skye (Figure 13-255), and between Canna and Sanday (Figure 13-256). The tombolo between Oronsay and 'mainland' Skye in Loch Bracadale contains a significant amount of olivine and pyroxene (Figure 13-255).

Beta version



Figure 13-255: Tombolo to Oronsay in Loch Bracadale to Skye.

Draft



Figure 13-256: Short tombolo between Canna (near) and Sanday (far), now bridged. In the distance is Oigh-sgeir.

Coastal sand dunes back a number of the bays, for example at Drumadoon Point on Arran (Figure 13-257; Figure 13-258), Kilmory on Rum, Laig on Eigg, Culnamean, Loch Brittle, Skye, and at the east end of Staffin Bay on Skye, where the adjoining dolerite cliffs are polished by sand blasting.



Figure 13-257: The sand dunes behind the present-day beach at Drumadoon, partially responsible for the excellent drainage of the Shiskine Golf Course, west Arran.

Beta Version



Figure 13-258: Sand dunes at Drumadoon providing the excellent drainage of the Shiskine Golf Course at Blackwaterfoot, west Arran.

Marine (tidal) notches are relatively common, where bedrock is eroded and undercut by wave action. One good example is on the NW coast of Ardnamurchan at Rubha Carrach (Figure 13-259); the low crags of Middle Jurassic Valtos Sandstone Formation in the Bay of Laig on the west coast of Eigg have, locally, been undercut (Figure 13-260).



Figure 13-259: Marine (tidal) notch, Rubha Carrach, NW Ardnamurchan.

Beta version



Figure 13-260: Marine (tidal) notch/undercut, Bay of Laig, west Eigg.



Figure 13-261: Marine (tidal) notch/undercut, Camas Sgiotaig, west Eigg.

13.16 Peat

High atmospheric moisture levels during the fifth millennium BP led to the decline of woodlands, as sites became waterlogged, and promoted the growth of blanket peat, which covers many hillsides to the present day. Extensive spreads of peat occur on the lava plateaux of Skye (Figure 13-262; Figure 13-263; Figure 13-264), Mull and Ardnamurchan (Figure 13-265), and in broad, ill-drained glens, for example Kinloch Glen on Rum. Peat was formerly an important source of fuel (Chapter 14). The pollen stratigraphy

Beta version

of peat provides a valuable record of climate change during the Quaternary (e.g. Lowe & Walker 1986, 1991).



Figure 13-262: Exposed bank of peat between the Lealt River and the dismantled railway that accessed Loch Cuithir (for diatomite) below the Trotternish Escarpment, Skye. Pole *ca*. 1 m long.



Figure 13-263: Exposed bank of peat between the Lealt River and the dismantled railway that accessed Loch Cuithir (for diatomite) below the Trotternish Escarpment, Skye.

Preview



Figure 13-264: Active peat cut, Suisnish, Strath, Skye.



Figure 13-265: Peat filled valley between Ben Hiant and Stallachan Dubha, Ardnamurchan.

13.17 Alluvium

Most streams in the mountainous areas have gravelly beds, and deposits of fine-grained alluvium are not extensive, partly due to the absence of major rivers. Small, elongate patches of alluvium occur next to many of the streams and rivers, and some of the broader valleys have more extensive deposits. Relatively large areas of alluvium are gradually encroaching on certain lochs, for example Loch Bà on Mull (Figure

13-266), Loch Coruisk in the Cuillin, Skye (Figure 13-267; Figure 13-268), and at Loch Cill Chroisd in Strath, Skye (Figure 13-269; Figure 13-270), where alluvium, lacustrine mud and vegetation are gradually filling the loch.



Figure 13-266: Loch Bà, Mull, where the River Clachaig deposits alluvium in a cone building out into the loch.



Figure 13-267: Loch Coruisk, Skye, where the Coruisk River deposits alluvium, building out into the loch.



Figure 13-268: Reworked gravel on the shore of Loch Coruisk.



Figure 13-269: Loch Cill Chriosd, Strath, Skye, in the process of being infilled by alluvium, lacustrine mud and vegetation.

Beta Version



Figure 13-270: Detail of Loch Cill Chriosd, Strath, Skye.

West of Kilchoan on the Ardnamurchan peninsula, Lochain Ghleann Locha is similarly in the process of being infilled by alluvium, lacustrine mud and vegetation (Figure 13-271).



Figure 13-271: Lochain Ghleann Locha, west of Kilchoan, Ardnamurchan, in the process of being infilled by alluvium, lacustrine mud and vegetation.

On Skye, there is an extensive tract of alluvium on the site of a former shallow loch at Eilean Chaluim Chille, north of Uig, which was drained in 1947 to give a large area of new pasture (Figure 13-272).

Beta version



Figure 13-272: Loch Chaluim Chille, the site of a drained loch. Below a thin discontinuous cover of peat and lacustrine sediments are raised marine deposits of Devensian age (*ca*. 25-30 m OD) comprising sand and gravel with (sea-) worn shells. View is towards the west from the main (A855) road.

There are many examples where terraces are cut into alluvium at more than one level, for example at the bottom of Glen Iorsa, Arran; farther up the glen, alluvium covers the valley floor for a distance of over 5 km above Loch Iorsa. Small placer deposits of heavy minerals occur in some rivers, with chromite-rich examples found on Rum in the Abhainn Rangail, Glen Harris.

Lacustrine deposits of diatomaceous earth occur in many places on Trotternish, north Skye, where they were worked in the past (Figure 13-273) (Chapter 14). The diatoms are the skeletal remains of unicellular plants that developed in freshwater lakes, most likely under warmer climatic conditions than at present. Extensive deposits of diatoms mixed with clay and peaty material occur at Loch Cuithir, *ca*. 6 km NNW of The Storr, where they overlie moraine deposits, and hence postdate the last glaciation, but are overlain by peat (Anderson & Dunham 1966). Diatomaceous earth is also known from near Knock on Mull and has been recorded on Eigg (Haldane *et al*. 1940).

Beta version



Figure 13-273: Hummocky ground at the base (east of) the Trotternish Escarpment, Skye, south of where the Staffin-Uig Road cuts across/through the escarpment. The prominent isolated hill is Cleat and the lochs are Loch Leum na Luirginn (nearest) and Loch Cleat (farthest). Such lochs are common along the base of the escarpment and have formed due to the impervious nature of the detritus that has formed by the landslip events and the presence of moraines. Note old peat cuts on the west (right) side of Loch Leum na Luirginn. View towards the SSE from the Staffin - Uig Road.

Near to the SW end of the promontory of Rubha an Dùnain on the east side of Loch Brittle, Minginish, Syke, a freshwater loch, Loch na h-Àirde, at < 3 m OD is connected to the sea by a narrow channel which has been modified and improved, most likely by the Vikings. The channel floods at high (Spring) tide, enabling, in times past, boats to be taken into the loch and, it is believed, act as a harbour/refuge and where they could be safely repaired (Figure 13-274).



Figure 13-274: Medieval canal linking Loch na h-Àirde with the sea, Rubha an Dunain, Loch Brittle. View is towards the north.

Pre-version

13.18 Aeolian deposits

Ballantyne (1998) describes aeolian deposits from the summit area of The Storr on Trotternish, north Skye. Up to 2.9 m thick, but more typically 0.5-1 m, and covering an area > 30,000 m^2 with an estimated volume of 41,000 m^3 (0.000041 km^3), these pale brown, high-level, vegetated deposits are identified as being largely intact (uneroded) and comprise very poorly sorted sands and silts with some gravel grade material (Figure 13-275; Figure 13-276). Ballantyne (1998) has investigated these deposits by extensive augering and temporary trenching. Natural exposure is limited to crescentic deflation scars close to the summit of The Storr, where uncommon frost-weathered boulders are revealed.

The thickness of these deposits decreases westwards, away from the broad summit of The Storr. To the east of the summit is the N-S -oriented escarpment formed by landslipping in the Holocene (see above). The derivation of the aeolian sediment is considered to be from this main escarpment cliff, with the material transported by upward, near-vertical airflow at the cliff, and subsequent westerly airflow towards and beyond the summit of The Storr. The sediment was subsequently trapped on the near-flat summit area of The Storr by slowly growing vegetation. Near-continuous accumulation is inferred by a lack of erosion surfaces within these deposits, although minor organic soils suggest waxing and waning of deposition.

Radio-carbon dating and pollen analysis indicate accumulation after 6,330-6090 years before present (BP) (Ballantyne 1998), with an average accumulation rate of 10-22 mm per century. Availability of sediment is attributed to fresh exposure of rock by the Holocene landslipping events which resulted in the formation of the main escarpment. Corylus, Pinus and Alnus (hazel, pine and alder) pollen are present within the sediments and are indicative of a wet climate, similar to today.



Figure 13-275: Crescentic scar exposing aeolian deposits near to the summit of The Storr, Trotternish, Skye.

Beta version



Figure 13-276: Aeolian deposits at the summit of The Storr, Trotternish, Skye.

13.19 Caves

Other than coastal caves associated with the Main Rock Platform (see above), caves and solution hollows have developed either where the Paleocene Beinn an Dubhaich Granite (Chapter 9) or a dolerite dyke (Chapter 7) has a contact with Cambro-Ordovician dolostones of the Durness Group (Chapter 2) in Strath, Skye.

A considerable network of passageways and caves has been accessed and thoroughly documented by Ryder (1974) (Figure 13-277).

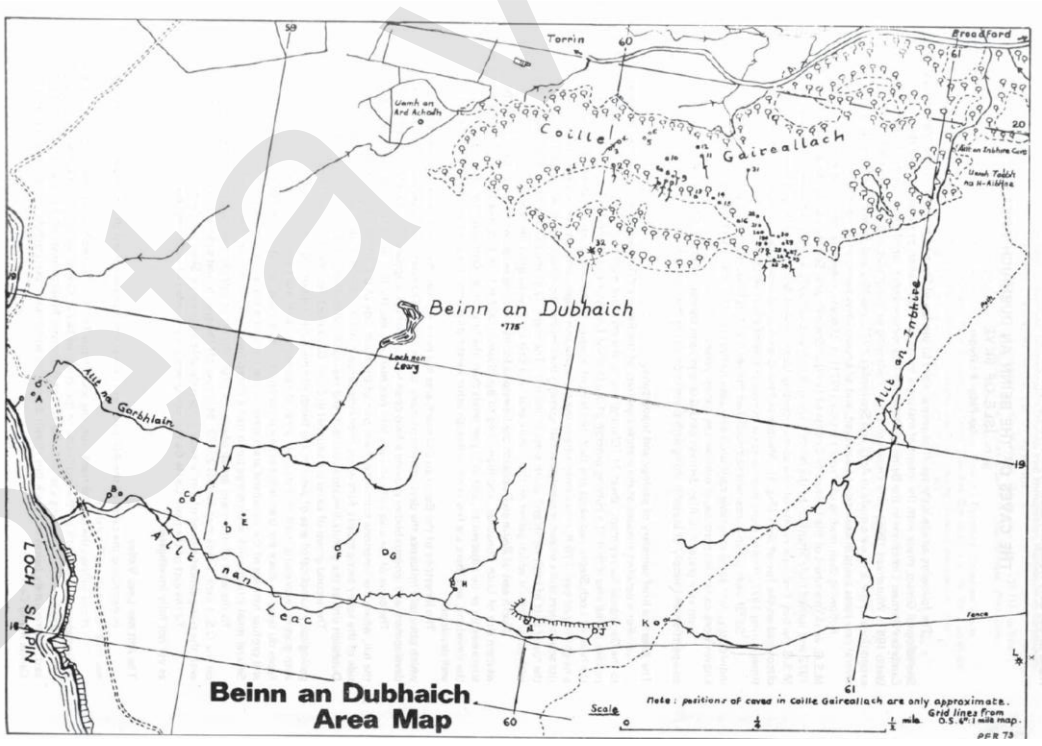


Figure 13-277: Location map of cave entrances in the Beinn an Dubhaich – Allt nan Leac – Kilchrist area, Strath. [Figure courtesy of Peter Ryder]

Beta version

One of the easiest entrances to locate is adjacent to the track which runs from Kilbride to the abandoned village of Suisnish at Suisnish Point. An obvious ‘sink’ is located west of the track, where the Allt na Garbhlain goes underground, to reappear at a ‘rise’ a short distance further to the SW (Figure 13-278; Figure 13-279; Figure 13-280).



Figure 13-278: Camas Malag Cave entrance, Strath.

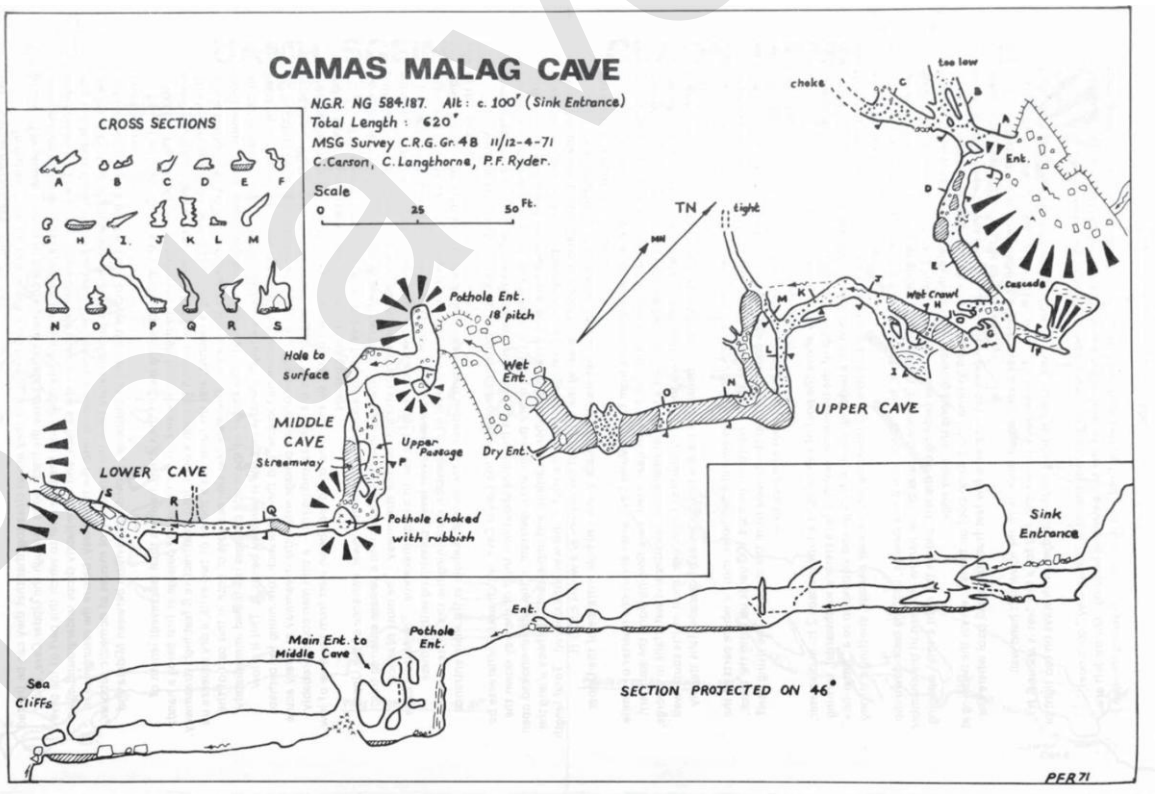


Figure 13-279: Camas Malag Cave map, Strath. [Figure courtesy of Peter Ryder]

Beta version



Figure 13-280: Camas Malag Cave, Strath. [Photograph courtesy of Peter Ryder]

Another cave entrance that can be identified and accessed relatively easily is Uamh an Ard Achadh ('High Pasture Cave'), located south of the Kilbride Road turnoff, in the verdant low ground below the ridge of Beinn an Dubhaich (Figure 13-281; Figure 13-282; Figure 13-283) To date, it is the longest cave at *ca*. 320 m, with a total vertical extent of *ca*. 12 m, with the entrance at an elevation of *ca*. 65 m OD.

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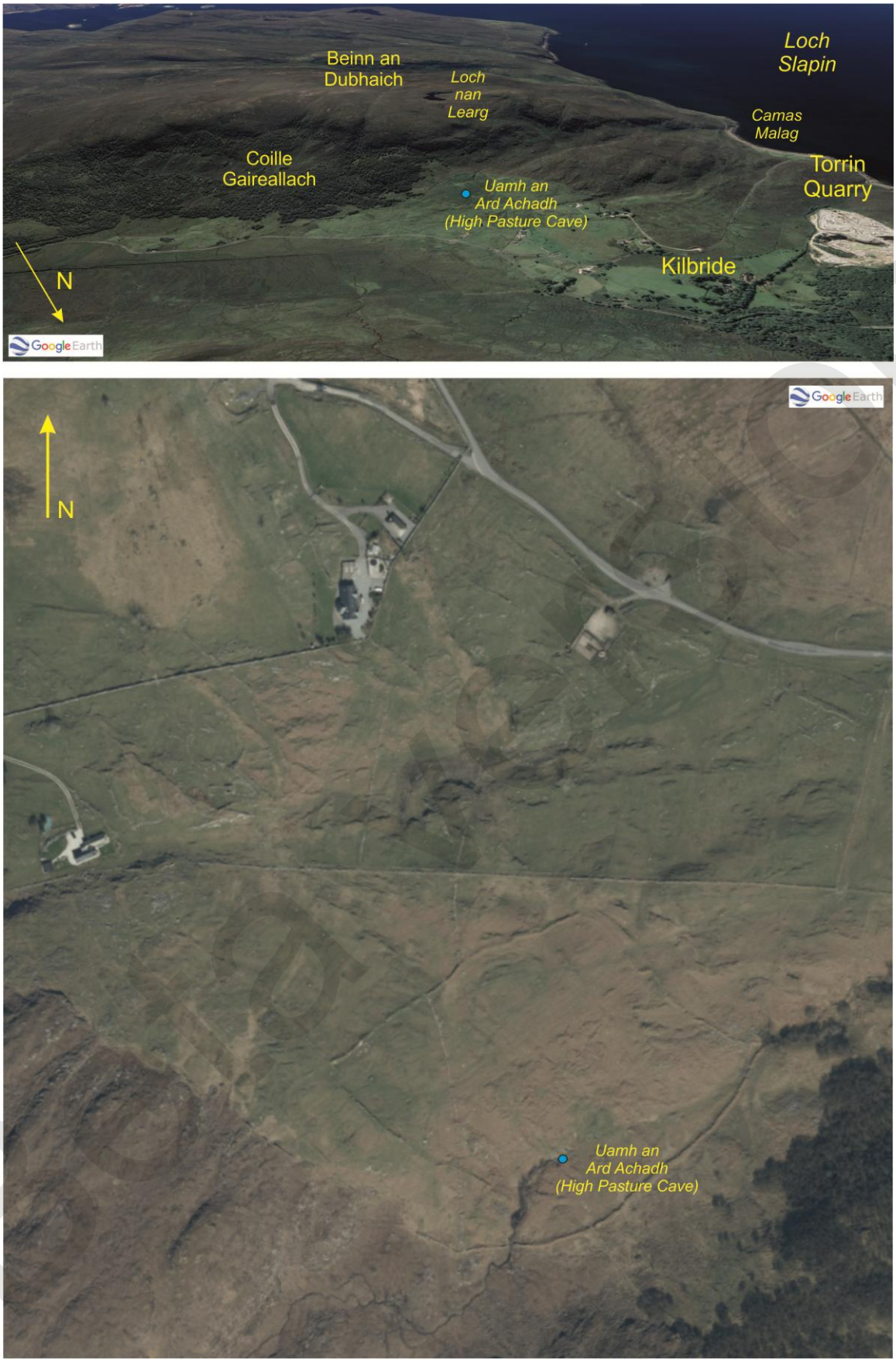


Figure 13-281: Uamh an Ard Achadh Cave, south of the Kilbride Road turnoff, Strath.

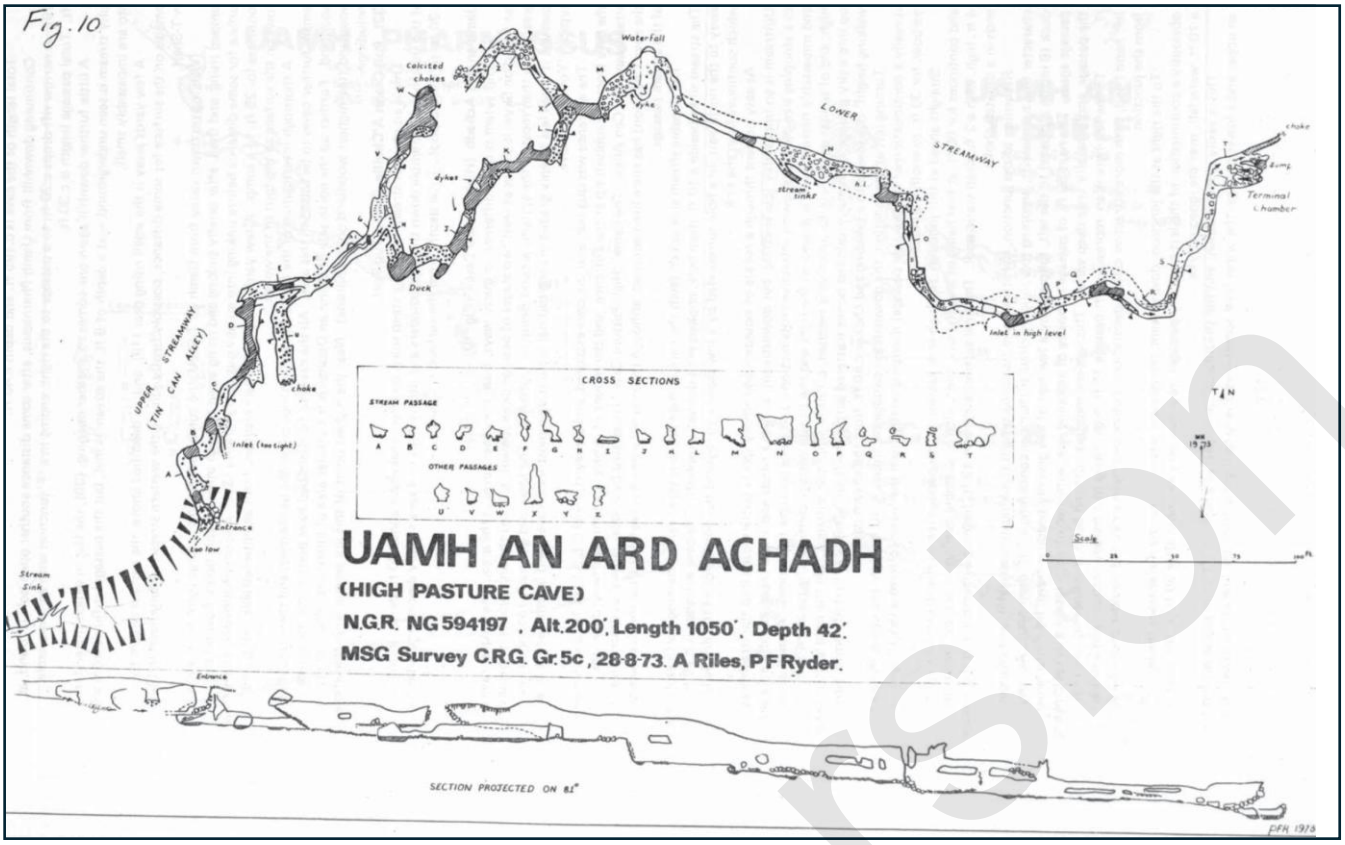


Figure 13-282: Uamh an Ard Achadh Cave, south of Kilbride Road turnoff, Strath. [Figure courtesy of Peter Ryder]

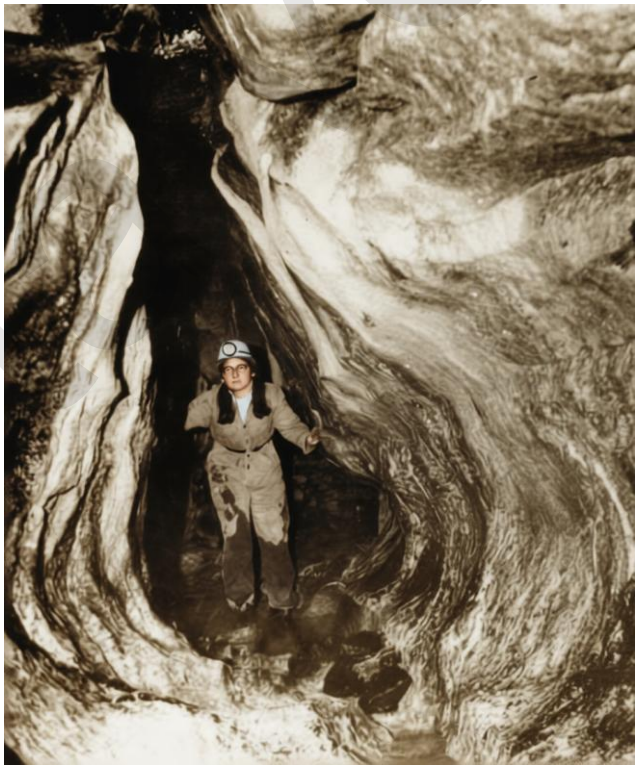


Figure 13-283: Uamh an Ard Achadh Cave, south of the Kilbride Road turnoff, Strath. [Photograph courtesy of Peter Ryder]

Better version

The Uamh Sluic Cave has a very obvious and large entrance, located north of the Allt nan Leac, *ca*. 20 m by 4 m, oriented NW-SE, and surrounded by relatively mature vegetation, most likely protected by the vertical sides of the entrance preventing overzealous grazing by sheep and cattle.



Figure 13-284: Entrance to Uamh Sluic Cave, north of the Allt nan Leac, Strath.



Figure 13-285: Entrance to Uamh Sluic Cave, north of the Allt nan Leac, Strath.

Better Version

13.20 Present day erosion

The significant increase in the tourist industry on Skye in recent years has had a significant impact on the landscape, with overused paths to some of the main 'attractions' (Figure 13-286; Figure 13-287). To avoid permanent damage will require an improvement in the overall infrastructure of the island.



Figure 13-286: Rapid erosion by apparently mindless tourists on the 'path' from the main road to the Old Man of Storr at the foot of the Trotternish Escarpment, Skye.

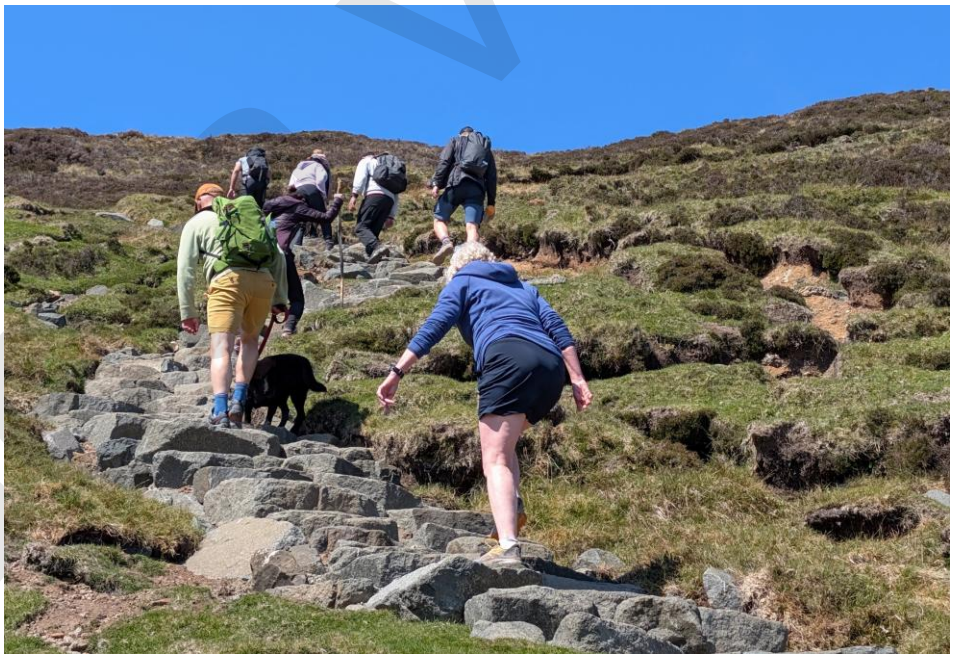


Figure 13-287: Blockwork path at the southern end of the Quiraing Escarpment, Trotternish, leading from the (pay) carpark to the top of the main cliff.

Beta version

14 Economic Geology

14.1 Introduction

The exploitation pattern of the limited economic resources of the district has undergone notable changes over the past 150 years. In place of a multiplicity of small-scale operations, the requirements for building materials and aggregate are now met by a few large concerns, and much of what was once obtained locally is now brought into the district, sometimes from considerable distances. Fuel requirements are met by imported oil, (bottled) gas and coal. Electricity is supplied to Mull, Skye and Arran by cable links to the Scottish Mainland and the only local contribution of any significance comes from the hydroelectric scheme at Loch Fada on Trotternish, Skye.

14.2 Iron

Carbonate-rich ironstone was obtained from the Lower Jurassic Raasay Ironstone Formation on Raasay, where the reserves were estimated at about 10 million tonnes. The chamosite-oolite ore occurs in beds up to 2.5 m thick between Churchtown Bay and Hallaig (Lee 1920). Both underground and opencast workings were employed and over 125,000 tonnes of ore were obtained during the active life of the operations, between 1916 and 1919 (Draper & Draper 1990). Remains of the workings are visible at several places in the south of Raasay. The Raasay Ironstone Formation also occurs on Skye, Ardnamurchan, Mull and elsewhere in the Hebrides but the beds are thin, generally of low quality and have not been exploited.

14.2.1 Raasay Ironstone Mine

The abandoned ironstone mine on Raasay was active during the First World War and provides an engaging story of the development of an economic resource on a relatively remote Scottish island. The iron ore was extracted from both surface outcrop and underground, processed and shipped to the Scottish Mainland to help fulfil demands caused by the war and the lack of material from abroad (Figure 14-1; Figure 14-2; Figure 14-3; Figure 14-4).



Figure 14-1: Remains of the Raasay ironstone mine infrastructure, East Suisnish, south Raasay.

Beta version



Figure 14-2: The Mine #1 entrance at the time of the mining operation.



Figure 14-3: The Mine #1 entrance after closure.



Figure 14-4:Flooded adit at entrance to Mine #1.

The publication *The Raasay Iron Mine (where enemies became friends)* by Laurence & Pamela Draper (1990) is an excellent account of the development of the opencast and mining operations and much of the summary, below, is attributed to this publication. The black & white photographs are from the British Geological Survey archive (codes P000038, 39, 41, 43, 44, 47 & 48).

It is useful to understand the formation of the ironstone (Figure 14-5; Figure 14-6; Figure 14-7; Figure 14-8; Figure 14-9; Figure 14-10; Figure 14-11; Figure 14-12; Figure 14-13). The Raasay Ironstone Formation is a chamositic ooidal ironstone that ranges from massive, through to thinly bedded, locally cross-bedded. It overlies a sequence of dark grey to black, organic-rich, micaceous mudstones (the Portree Shale Formation) with sparse benthic fossils (Chapter 3). Combined, these two units are typically 5-6 m thick. They are of Lower Jurassic age (Toarcian; 174-183 Ma) and overlie shallow marine siltstones and sandstones of the Scalpay Sandstone Formation. The overlying Bearreraig Sandstone Formation marks a return to significant coarse clastic sediment input to the basin and was deposited in a shallow marine environment.

Deposition of the Portree Shale Formation and the Raasay Ironstone Formation occurred throughout the Hebrides Basin, although are best developed (or at least recognised) on Raasay and north Skye. Ironstones of similar age occur elsewhere, for example the Cleveland Basin of NE England. Formation of the Raasay Ironstone Formation is considered to have taken place during one of the two main Phanerozoic ironstone-forming periods in shallow marine subtidal to intertidal waters during a period of sea level change and negligible clastic sediment input. Ammonites and belemnites are relatively common and confirm a marine environment of deposition. Weathering was important at this time, facilitated by the Toarcian warm humid climate, producing iron-rich waters delivered into the basin. The dominance of

Pre-ver

chamosite (an Fe-rich chlorite) ooids in a calcium carbonate matrix, together with cross-stratification, indicate the important role of intertidal currents during their formation. Other indicators of a shallow water depositional environment include the (uncommon) presence of crinoids and stromatolites.

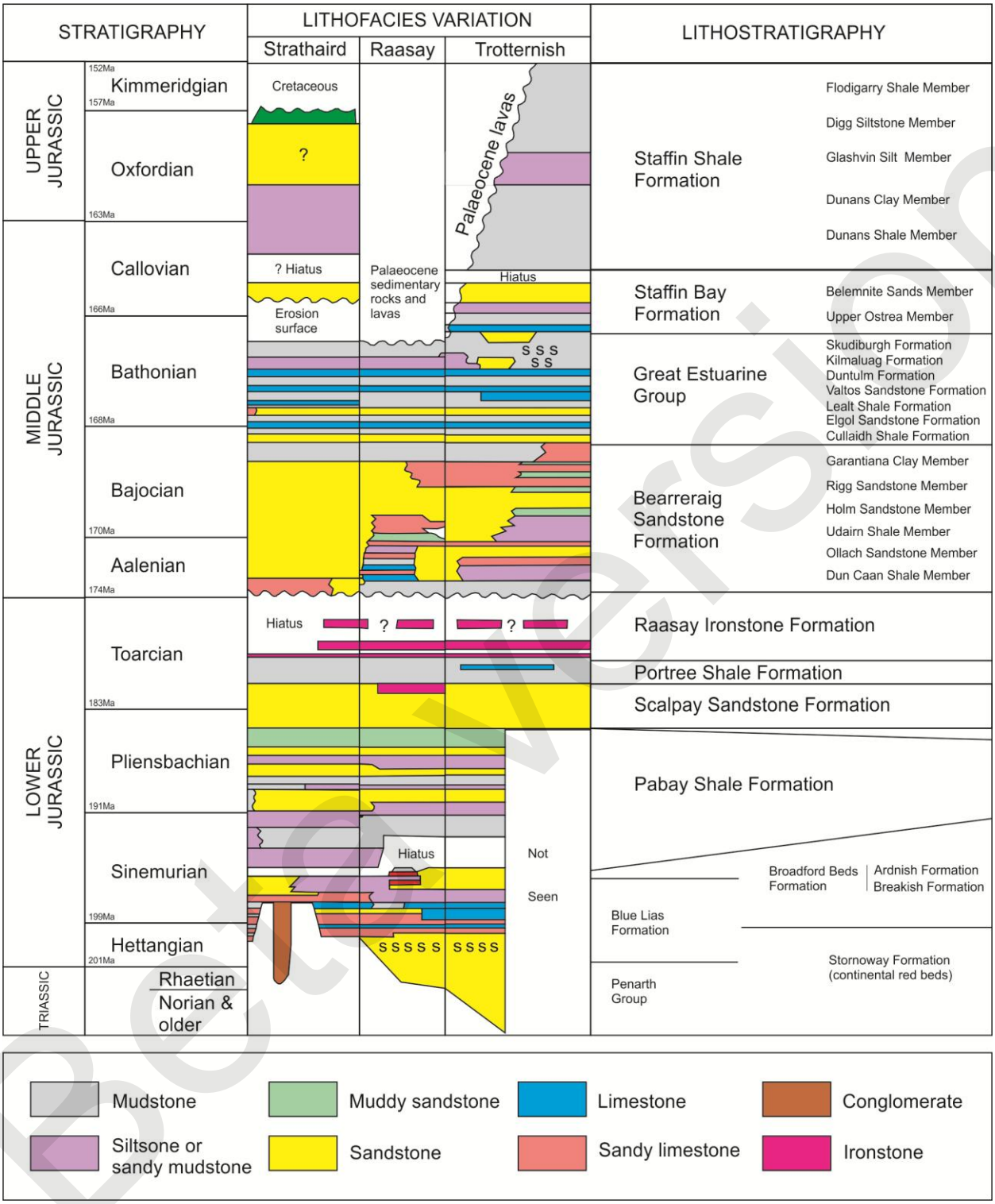


Figure 14-5: Stratigraphy of the Jurassic within the Hebrides Basin.

Beta version

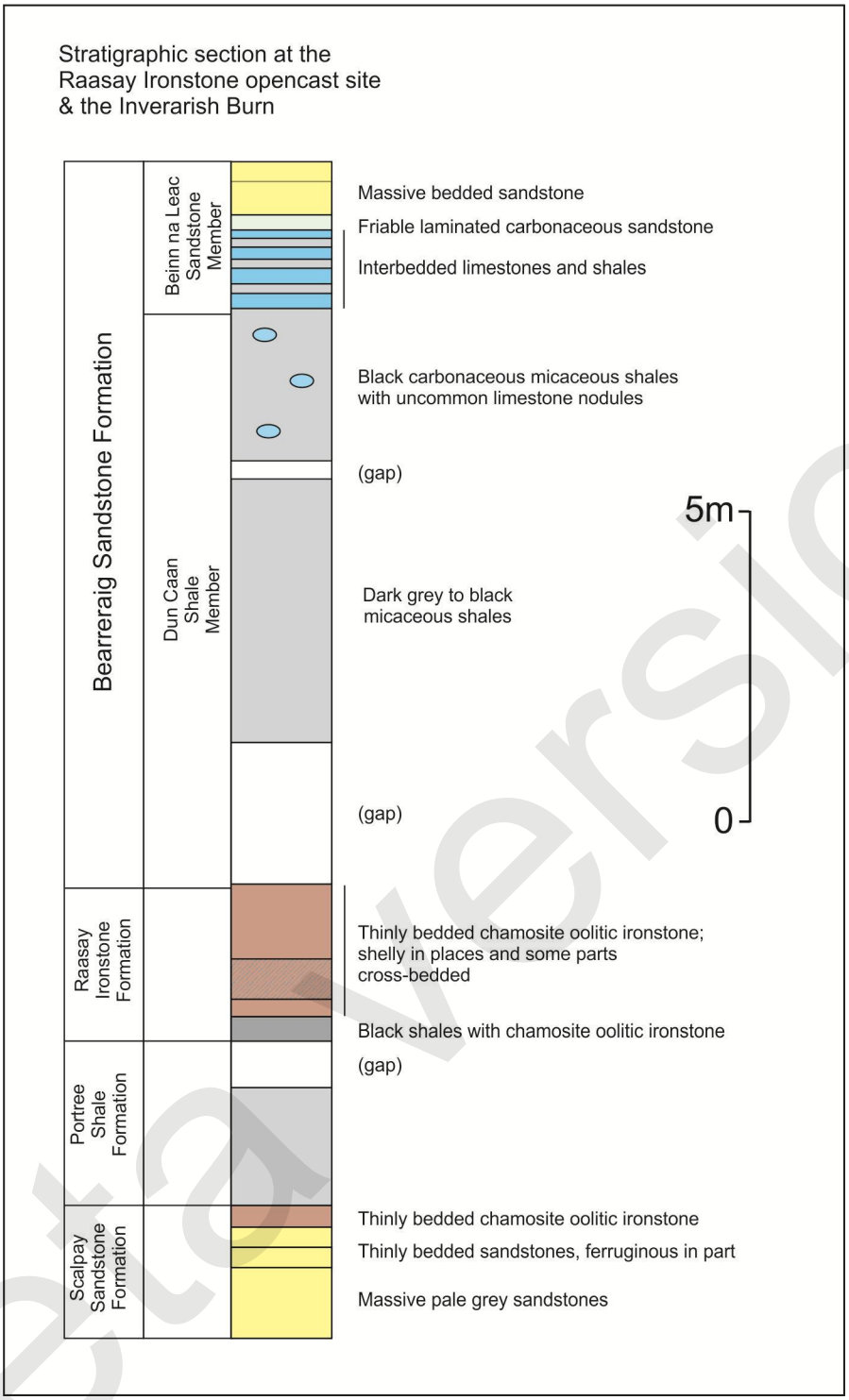


Figure 14-6: Details of the stratigraphy of the Raasay Ironstone Formation, together with underlying and overlying strata.

Beta version



Figure 14-7: Photomicrograph of the Raasay Ironstone Formation chamositic ooidal ironstone with echinoderm fragments in a carbonate matrix/cement. Image *ca.* 5 mm across. View under plane polarised light.

Discovery of the Raasay Ironstone Formation

The Raasay Ironstone Formation was discovered with sleuth-like tenacity by Horace B. Woodward of the British Geological Survey in 1893. References to earlier observations are difficult to substantiate. Exposures are rare and it was where the outcrop crosses the Inverarish Burn that the discovery was made. Prior to the development of the mine, the distribution of the ironstone was determined by exploratory (manually drilled) boreholes. A typical and workable thickness of *ca.* 2 m was recorded and an estimated 10 million tons of extractable material determined.

Exploitation of the ironstone was restricted to Raasay, where it has an outcrop and an extensive subcrop, albeit of variable thickness (or is not present). It is typically very poorly exposed and has no commercial value (in the context of the early 20th Century) except in the area NE of Inverarish (the sole village on Raasay). The lack of good exposure is in part due to the ironstone's relatively rapid decomposition when directly exposed to the atmosphere. When fresh it is dark green, but upon exposure, or near (< 5 m) to the Earth's surface, the carbonate within it is leached out and oxidation occurs, producing a dull rusty brown material. Typical fresh (green) ironstone has an iron content of 20-30%, whereas weathered/altered (brown) material is somewhat enriched. The presence of calcium carbonate within the ironstone is advantageous with respect to its processing.

Beta version

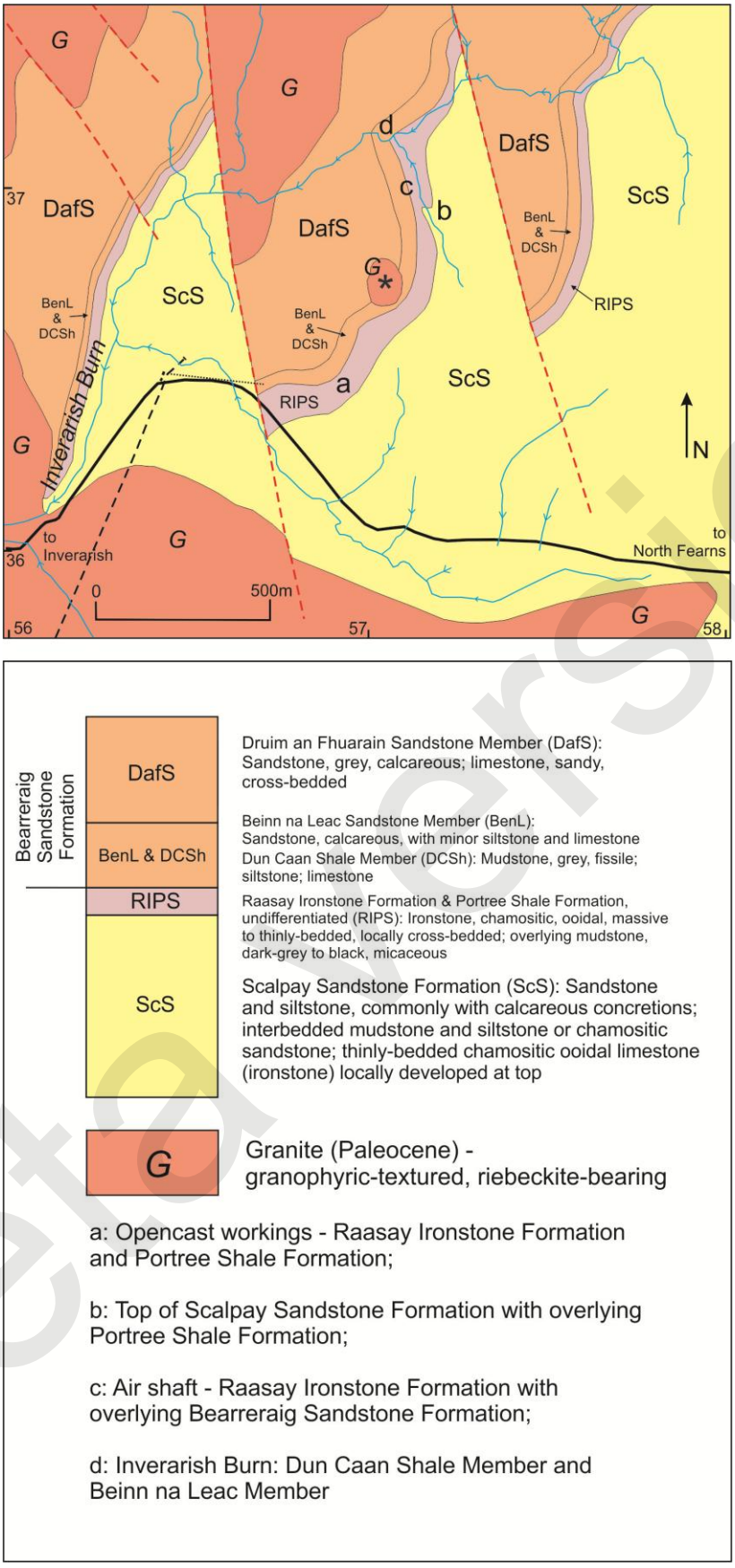


Figure 14-8: Simplified geological map and stratigraphic details of the opencast area and mine in the vicinity of the Inverarish Burn.

Beta version

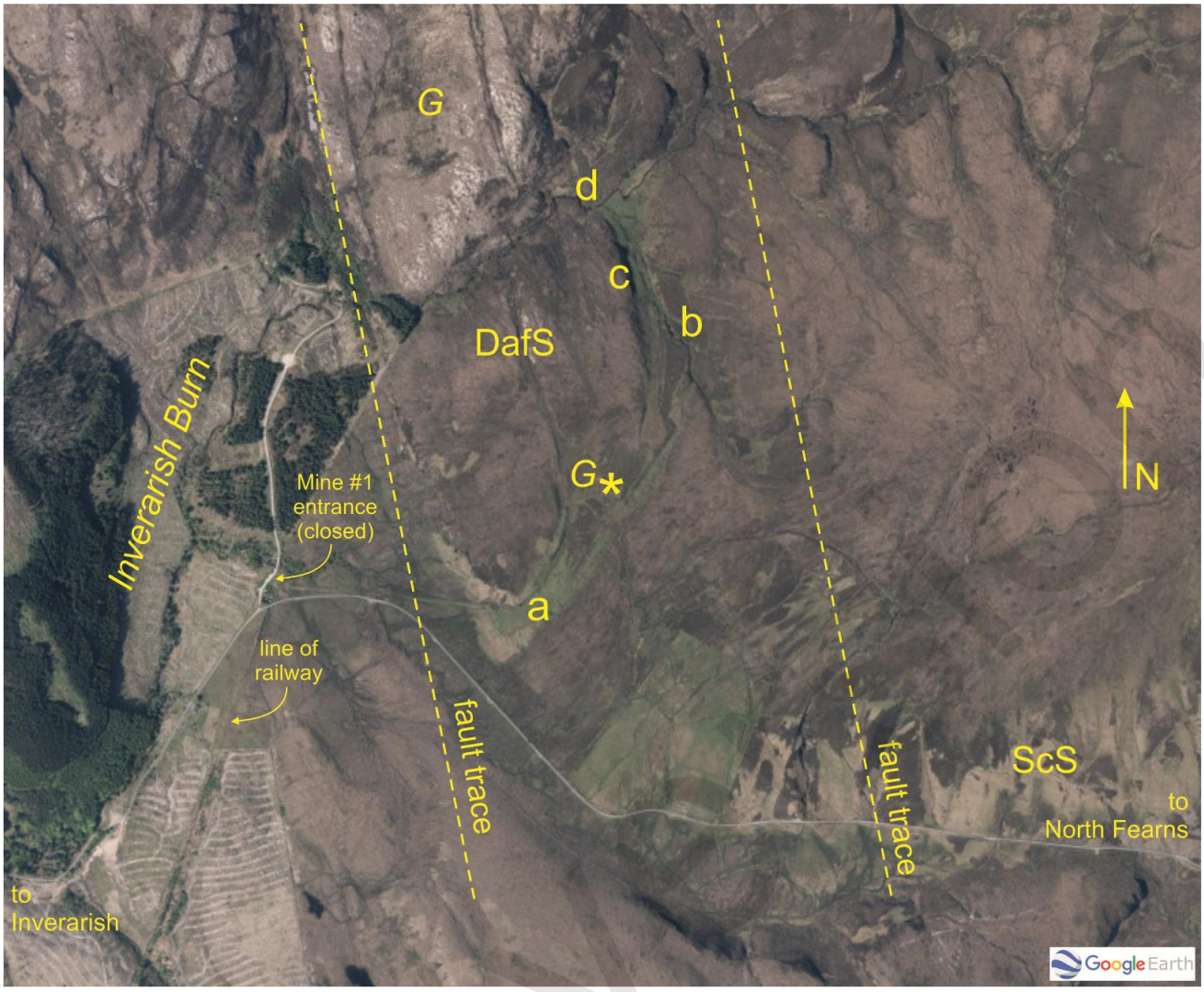


Figure 14-9: Annotated Google Earth® image of the opencast area (a, b, c & d) and Mine #1 entrance in the vicinity of the Inverarish Burn.

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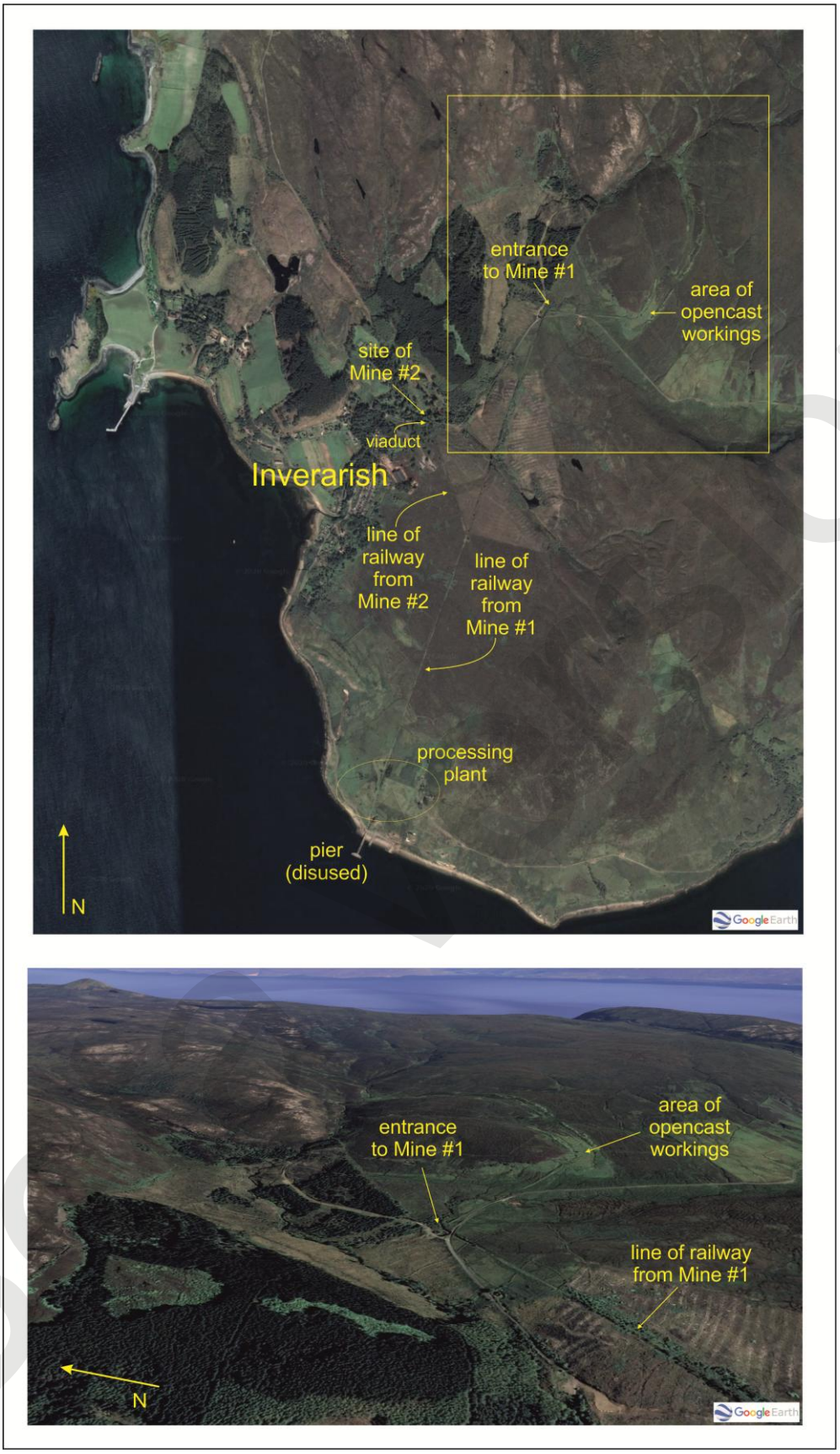


Figure 14-10: Annotated vertical and oblique Google Earth® images of the area involved in the exploitation of the Raasay Ironstone Formation, including the opencast area and Mine #1 in the vicinity of the Inverarish Burn.



Figure 14-11: Opencast area, east of entrance to Mine #1. Above the outcrop of inclined Raasay Ironstone Formation strata are (overburden) spoil heaps. View towards the north.



Figure 14-12: Exposure of Raasay Ironstone Formation strata at the opencast area. Pole *ca*. 1m long.



Figure 14-13: Detail of Raasay Ironstone Formation strata at the opencast area. The pale green 'cores' are fresh material, surrounded by a boxwork of rusty-brown weathered (oxidised) material. Ruler 30 cm long.

Development of the opencast site and mine(s)

Initial serious interest to exploit the Raasay ironstone can be traced back to 1910, when William Baird & Company Ltd of Glasgow, with interests in iron and coal, approached the then proprietor of Raasay, Wallace Thorneycoft, a mining engineer and coal mine owner with an interest in geology, to determine the extent of the reserves and subsequently sell (them) the estate (in 1911). Documentation of the development of the opencast and mining operations is good (see above) and of interest (Figure 14-14; Figure 14-15; Figure 14-16; Figure 14-17; Figure 14-18; Figure 14-19; Figure 14-20; Figure 14-21; Figure 14-22).

The initial stage of the mining activity was the extraction of ore from the surface outcrop. Two mine entrances were identified (Mine #1 & Mine #2) and infrastructure was gradually installed. For Mine #1, which ultimately was the sole underground entrance, a straight double-track narrow-gauge (2'3" or 0.7 m) cable-haulage rail, *ca*. 2.5 km long, was built to the coast at the newly constructed pier (specifically for the mining activity) at East Suisnish, where the processing plant, including kilns, was also built). Prior to the completion of the railway, ore was transported by horse and cart to the old pier at Clachan.

Beta version



Figure 14-14: Trial adit into the Raasay Ironstone Formation located at the top of the incline in the area where opencast production occurred. Note rail head. Person for scale. [BGS P000039]



Figure 14-15: Information boards close to the entrance to Mine #1 and derelict main hauler house.

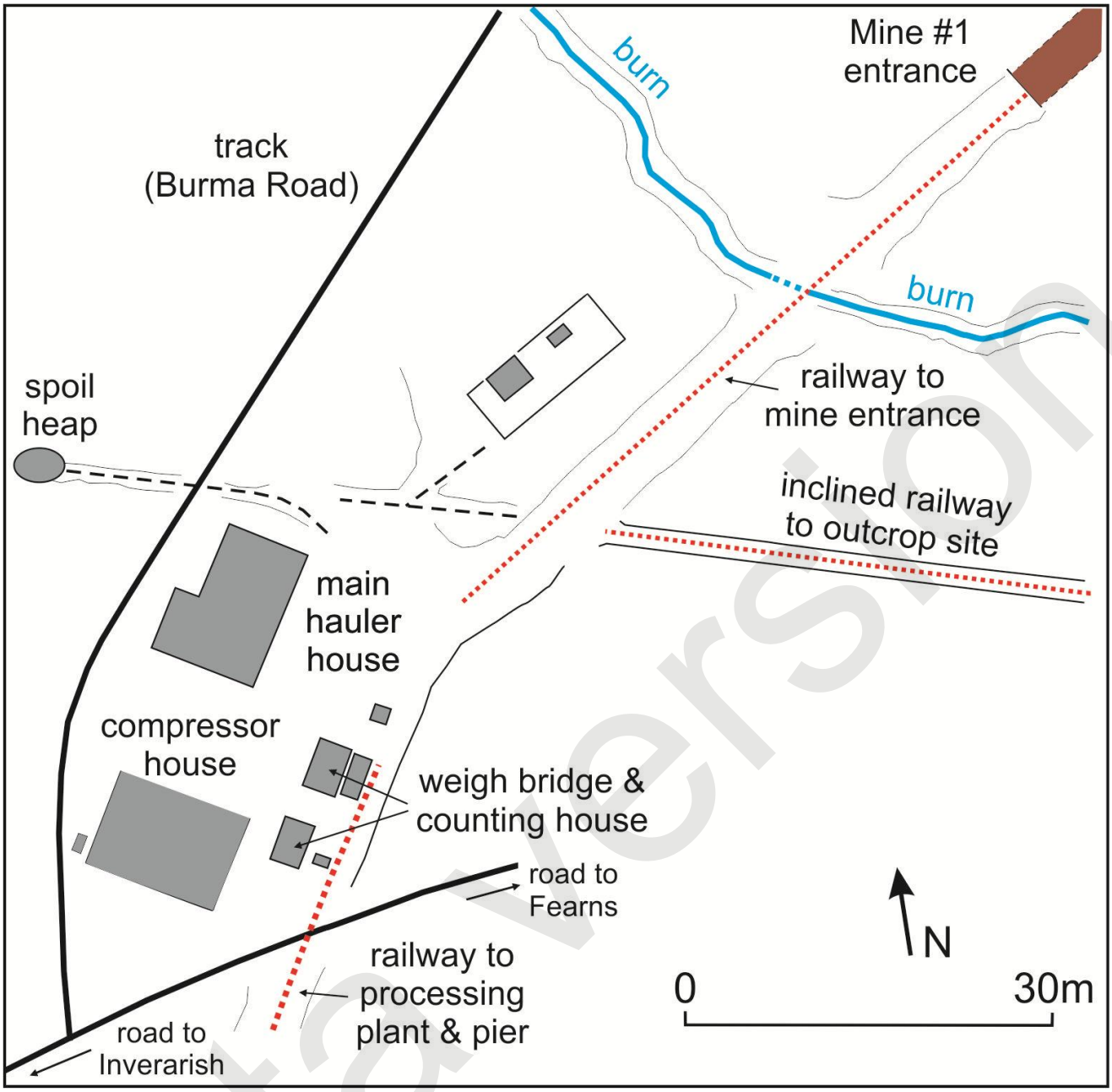


Figure 14-16: Sketch plan of area around entrance to Mine #1.

Beta version



Figure 14-17: Derelict main compressor house, near to entrance to Mine #1.



Figure 14-18: Information boards close to the entrance to Mine #2.



Figure 14-19: Entrance to Mine #2. This mine was not productive due to unforeseen geological complexities, most likely faults. The site was later used as a sawmill for the production of pit props, rail sleepers and power poles. [BGS P000041]



Figure 14-20: Derelict building close to the entrance to Mine #2.

Provisional version



Figure 14-21: A Bucyrus Steam Dragline ('Steam Navvy') near to the entrance to Mine #1, used to remove superficial material from the area developed for opencast extraction. [BGS P000047]



Figure 14-22: Detail of Bucyrus Steam Dragline ('Steam Navvy') near to the entrance to Mine #1, used to remove superficial material from the area developed for opencast extraction. Note armed guard, suggesting that at least some of the workers perched on the dragline are German prisoners-of-war. [BGS P000048]

The processing plant at East Suisnish was constructed by Robert McAlpine & Sons and comprised a crusher (where coal was added), kilns to calcine (roast, to create a concentrate) the ironstone, and a large

hopper to store processed material prior to shipping. Not all the ore was processed on the island, with some shipped directly after passing through the crusher (Figure 14-23; Figure 14-24; Figure 14-25; Figure 14-26; Figure 14-27; Figure 14-28).

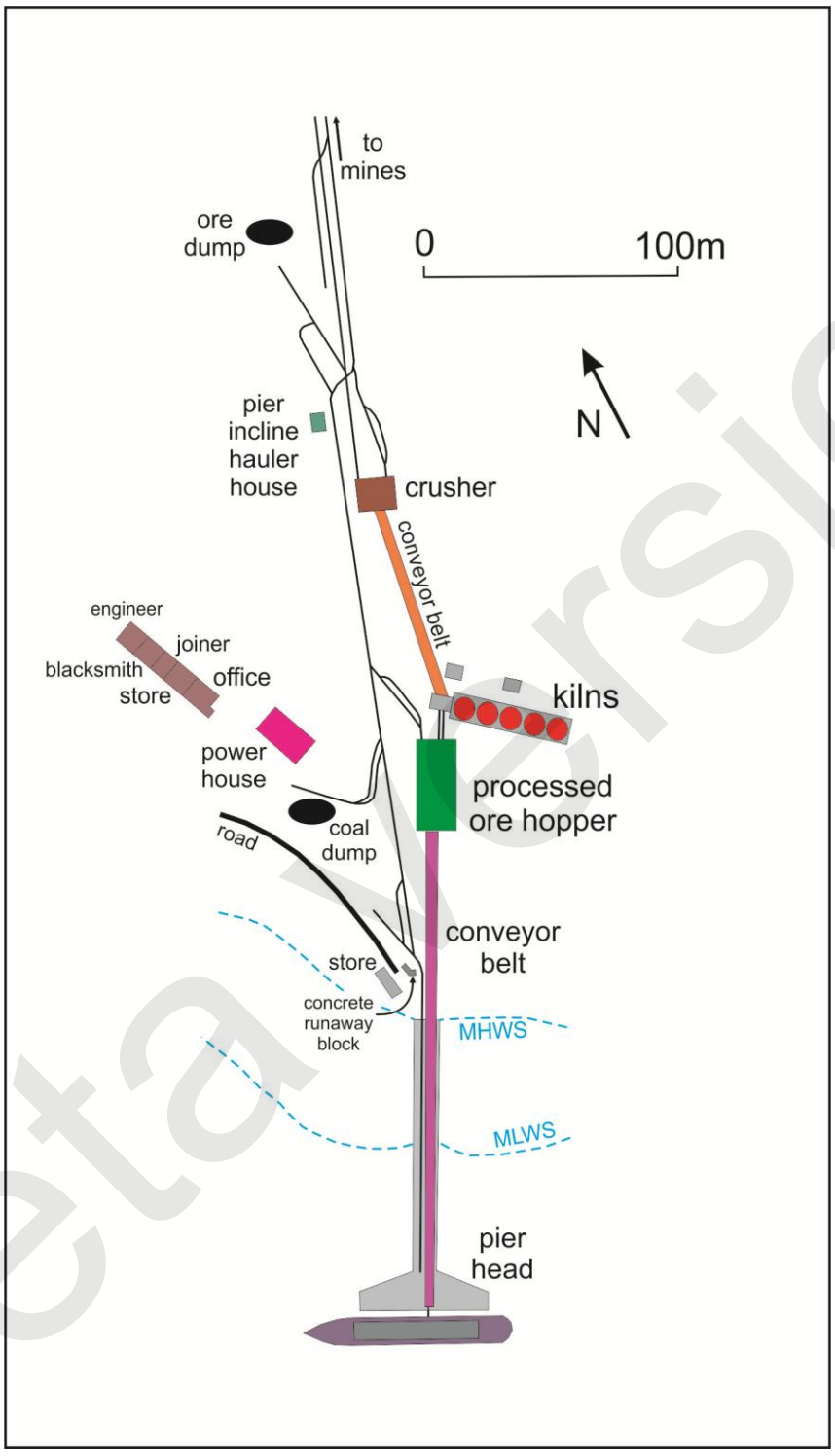


Figure 14-23: Layout of the processing plant.

Other onsite facilities included an office for administration staff and workshops for joiners, blacksmiths and engineers. Dynamite and detonators were stored in a remote stone building surrounded by a blast bank. There was a lightening conductor on the roof.

Beta Version



Figure 14-24: Processing plant at East Suisnish, viewed towards the east. At the top of the short rail incline is the pier hauler incline house, to the right of which is the crusher (arched roof) and conveyor to the top of the kilns. Coal was taken to the crusher via the short rail incline, where it was mixed with the unprocessed ore and thence to the kilns. The white building, to right, comprises offices, stores and workshops for joiners, blacksmiths and engineers. [BGS P000044]

Beta version



Figure 14-25: Pier and processing plant at East Suisnish, including five cylindrical calcining kilns, store (to left of pier), coal dump and storage hopper (with arch roof). At the top of the short rail incline is the Pier Hauler Incline House, to the right of which is the crusher with a conveyor to the top of the kilns. Coal was taken to the crusher via the short rail incline, where it was mixed with the unprocessed ore and thence to the kilns. [BGS P000043]

Beta version



Figure 14-26: Remnants of main cable railway above the main processing plant at East Suisnish and the ore shipping pier, beyond. View south towards Skye.



Figure 14-27: Derelict base to the kilns, uphill from the ore hopper, East Suisnish. View south towards Skye.

Private version



Figure 14-28: Ore hopper within the processing plant, East Suisnish. View towards the NE.

Opencast mining commenced in August 1916, involving the stripping of overburden from the area to the east of the entrance to Mine #1 by a Bucyrus Steam Dragline ('Steam Navvy'), with the ironstone then extracted using two Bucyrus Rev Shovels. Material was conveyed via a two-stage cable-haulage rail to the processing plant at East Suisnish, first on a single-track from the opencast area to near to the entrance of Mine #1 and then via its double-track cable-haulage rail, downhill to the processing plant.

The underground mining operation also commenced in the Summer of 1916. The electrically driven cable-haulage system from near to the entrance to Mine #1 was the main transport mechanism, involving wagons ('hutches') that were attachable to the haulage cable, allowing them to be safely transported downhill full of ore, and back to the mine entrance to collect further material.

The track from the failed Mine #2 joined the main (Mine #1) track via a single-track at a junction downhill from the entrance to Mine #1, where ore would be transferred to the 'main' line. However, due to geological complexities not identified prior to the initiation of Mine #2 it was not able to provide a significant amount of ore and was abandoned.

The drop in height of the main haulage track is *ca*. 120 m over the *ca*. 2.5 km from the mine to the processing plant. Where it approached the processing plant, it was diverted around a large concrete block, installed to stop any runaway wagons. A variety of embankments and cuttings were constructed to produce the constant gradient of the 'main' line from the Mine #1/#2 junction. Two viaducts were also necessary; one over a gully close to the entrance to Mine #1 and a second where the spur line to Mine #2 crossed the Inverarish Burn and the road out to Fearns.

Beta version

Mining involved the traditional room and pillar (or bord and pillar) technique. First, two adits (tunnels; one for extraction, the other for ventilation and access for the miners) were driven (excavated), *ca*. 14 m apart from the Mine #1 entrance, NE for *ca*. 300 m to the main extraction area. From here, a quasi (N-S & E-W) grid system of 'rooms' was excavated (i.e. the ore that was removed, leaving the pillars to support the roof). Ore was not extracted fully to the top of the Raasay Ironstone Formation stratum; the locally developed overlying Dùn Caan Shale Member was unstable and capable of collapsing, so a *ca*. 0.3 m thickness of ironstone was left *in situ,* enabling a thickness of *ca*. 2 m to be removed. The overall gradient of the floor of the mine (adits and extraction 'rooms') was *ca*. 1 in 100 towards the SW, which aided water drainage from the mine and removal of the ore in wagons to the mine entrance.

Extraction involved drilling and blasting, followed by removal on an evolving underground rail system to the mine entrance. The workers operated a three-shift system: drilling from late afternoon until late evening; blasting during the night; and extraction of the ore during the day. British miners worked the drilling and blasting shifts, with German prisoners-of war (see below) working the daytime extraction shift. Lighting was primitive, using small oil lamps, attached to the miners' helmets.

A weigh bridge at the top of the main line recorded the amount of ore extracted. An estimated 12,000 tons of ore were extracted from the opencast site, compared to *c*. 150,000 tons from the underground operation.

Houses for the workers were constructed in Inverarish, comprising four terraces, each of sixteen houses. In addition, Churchton House and Suisnish House were built at this time, also for employees of William Baird & Company Ltd.

Extraction of ore was delayed for a variety of reasons, the main one being the start of World War 1 and its significant impact on the availability of suitable workers. However, the difficulties of obtaining suitable iron ore from outside the UK at this time caused the Government to investigate and back the extraction of Raasay ironstone to help with the war effort. After much discussion it was agreed that William Baird & Company Ltd should manage the operation on behalf of the Government and that German prisoners-of-war would be made available to partially man the operation.

Necessary security was be put in place by the British Army for the duration of the mining. Funding was provided for any outstanding construction and infrastructure costs, including repairs to and depreciation of the plant. Prisoners-of-war started to arrive in mid-1916 and rose to *c*. 250, with a further *c*. 60 Britons involved, some from Raasay, others from elsewhere in the United Kingdom. Most of the Germans were selected based on appropriate mining and other skills and were housed in the suitably fortified Inverarish terraced houses. Worker unrest in early 1917 occurred due to significant wage disparities between the Raasay workers and those from elsewhere, and also grievances due to the presence of the German prisoners-of-war workers. These issues were resolved early in 1918 by an increase in pay, although friction continued, and various minor disputes erupted from time-to-time.

End of the Mining Activity

A significant fall in demand for iron occurred after the end of World War 1 and the UK Government moved to shut down the Raasay production in early 1919. Repatriation of the prisoners-of-war was completed by early 1920. Meanwhile, twelve of the Germans died during the 1918-19 Spanish flu pandemic. A further two of the prisoners-of-war had died because of accidents whilst involved in the mining operations.

William Baird & Company Ltd sold the estate in 1921-22 to the Scottish Board of Agriculture. Thereafter, the natives of Raasay were able to access land suitable for crofting. Soon after, a small amount of mine

Beta version

infrastructure material was removed from the island. However, the main plant was kept on a care-and-maintenance basis, with the thought that production may again be required. This did not happen and by 1941 it was determined that, because of the availability of cheaper ore from elsewhere, the mine and all its plant be abandoned. Salvageable material, for example the kilns, was removed and transported off the island to be used elsewhere. The present-day state of the buildings and other infrastructure is the result of removal of materials useful elsewhere on the island and natural degradation over the decades.

14.2.2 Clay-ironstone

Clay-ironstone of Carboniferous age was obtained from sedimentary rocks near Corrie, Arran, and is reputed to have been exported to the Scottish Mainland. Elsewhere on Arran, there are signs of workings and smelting involving bog iron-ore. The magnetite-bearing skarns close to the margin of the Beinn an Dubhaich Granite on Skye were examined during the Second World War (1939-45) but the deposits, which are associated with small amounts of copper mineralisation, were not exploited.

14.3 Chromium, magnesium and precious metals

Substantial amounts of chromite and forsteritic olivine are present in shallow water marine sands off southern Rum (Figure 14-29) and in Loch Scavaig, Skye (Basham *et al.* 1989). Although the chromite tends to be iron-rich compared with ores in current commercial use, the abundant, associated magnesian olivine may be of value as an abrasive. The deposits in Loch Scavaig are mixed with glacial clays, which would make exploitation difficult, but those off Rum could easily be recovered. The sources of the chromite and olivine are the layered, olivine-rich ultrabasic rocks of the Rum and Skye central complexes, where chromite occurs in seams and layers generally less than 1 cm thick (Figure 14-30; Figure 14-31). It is commonly associated with sulphide minerals and the ultrabasic rocks on Rum, Skye and Mull show generally elevated levels of the platinum-group elements (Butcher *et al.* 1999; Pirrie *et al.* 2000). On Rum, electrum (an Au-Ag alloy; Dunham & Wilkinson 1985), and platinum-group minerals are associated with the chromite seams (Butcher *et al.* 1999). The platinum-group minerals are also found as a minor constituent of small, chromite-rich placer deposits in streams on Rum. These primary and alluvial deposits are too small to be of direct commercial interest and, furthermore, they occur in environmentally sensitive localities; nonetheless, their paragenesis has proved to be of considerable interest (e.g. Power *et al*. 2003).

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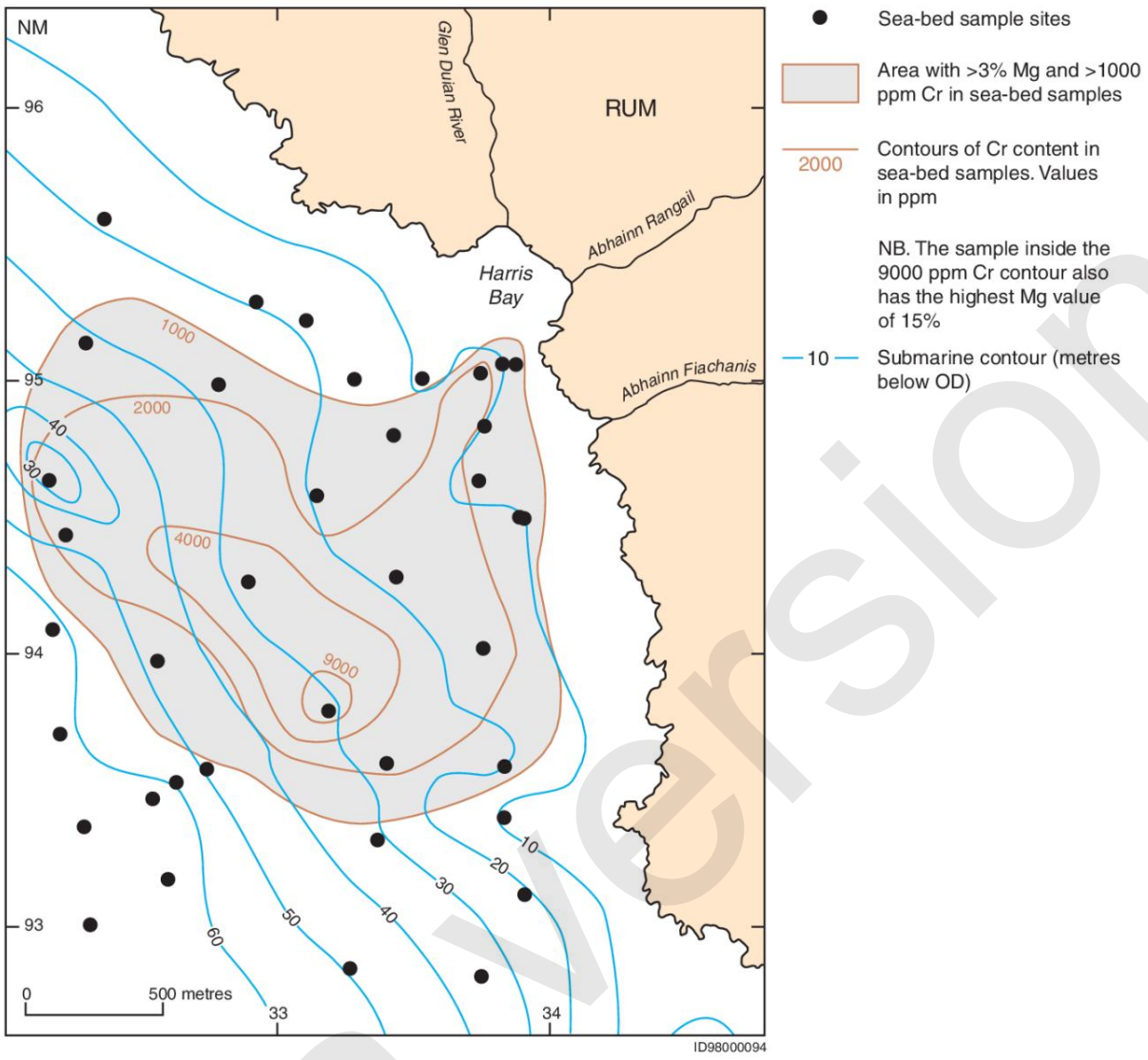


Figure 14-29: Chromium and magnesium distribution in the superficial marine sediments off Rum (after Emeleus 1997).

Beta version



Figure 14-30: Chromite seams along the boundary between pale anorthositic troctolite and dark peridotite at the base of Unit 8 of the Eastern Layered Intrusion, Bealach Bairc-mheall (between Barkeval and Hallival). [Photograph courtesy of David Brown]

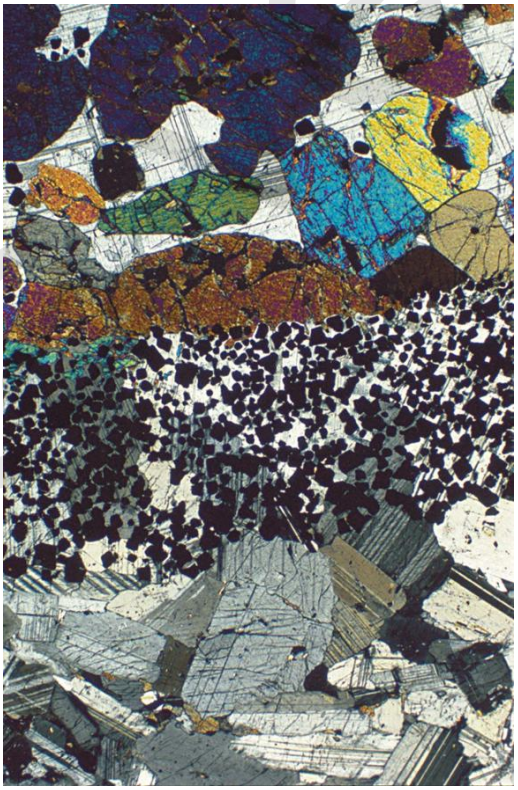


Figure 14-31: Chromite-rich seam at contact between anorthositic bytownite-troctolite (an extreme plagioclase-dominated cumulate) of Unit 11 (below) and feldspathic peridotite of Unit 12, Eastern Layered Intrusion, NE Hallival, Rum. [Photograph courtesy of Henry Emeleus]

Beta version

14.4 Vein deposits

Good quality baryte has been obtained from a system of north-trending veins in Glen Sannox on Arran (Figure 14-32; Figure 14-33; Figure 14-34; Figure 14-35; Figure 14-36; Figure 14-37; Figure 14-38; Figure 14-39; Figure 14-40; Figure 14-41; Figure 14-42). The veins are up to 3 m wide and are hosted by Lower Old Red Sandstone strata near to the margin of the Paleocene North Arran Granite Pluton (Chapter 9), although it is unlikely that there is any genetic connection with the granite. Imprecise K-Ar dates suggest a Triassic age (Moore 1979). Several hundred tonnes of ore were raised each year for over 20 years up to 1862, when working ceased. Extraction resumed in 1918, with annual production sometimes exceeding 8000 tonnes of barytes before the mine was abandoned in 1944.



Figure 14-32: View of the baryte workings in Glen Sannox, NE Arran in 1922.

Beta Print



Figure 14-33: Abandoned baryte mine workings, Glen Sannox. View towards SW.



Figure 14-34: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359399].



Figure 14-35: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359377]



Figure 14-36: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359415]

Preliminary



Figure 14-37: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359404]



Figure 14-38: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359374]



Figure 14-39: Line of (lifted) track associated with the abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2359392]



Figure 14-40: Abandoned baryte mine workings, Glen Sannox, NE Arran. [Sannox Barytes Mine, taken Sunday, 10 April, 2011cc-by-sa/2.0 © Ashley Dace – geograph.org.uk/p/2358898]



Figure 14-41: Barytes, Glen Sannox.



Figure 14-42: Barytes, Glen Sannox.

Analyses of stream sediment samples close to the southern margin of the North Arran Granite Pluton show enhanced levels of tin, tungsten, uranium and thorium, and cassiterite has been recovered from sediments in the Glen Sannox River suggesting the presence of mineral veins in the granite or its host rock.

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14.5 Gemstones

Small, impure sapphires have been obtained from hornfelses adjoining a major ring-intrusion at Glebe Hill, Kilchoan, Ardnamurchan (Richey & Thomas 1930). Sapphire has also been recovered from xenoliths within tholeiitic basalt and dolerite sills at Loch Scridain and Carsaig, Mull Figure 14-43; Figure 14-44), where these aluminous, sapphire-bearing accidental xenoliths/inclusions were derived from Moine Supergroup pelitic rocks (Dempster *et al.* 1999; Chapter 8).

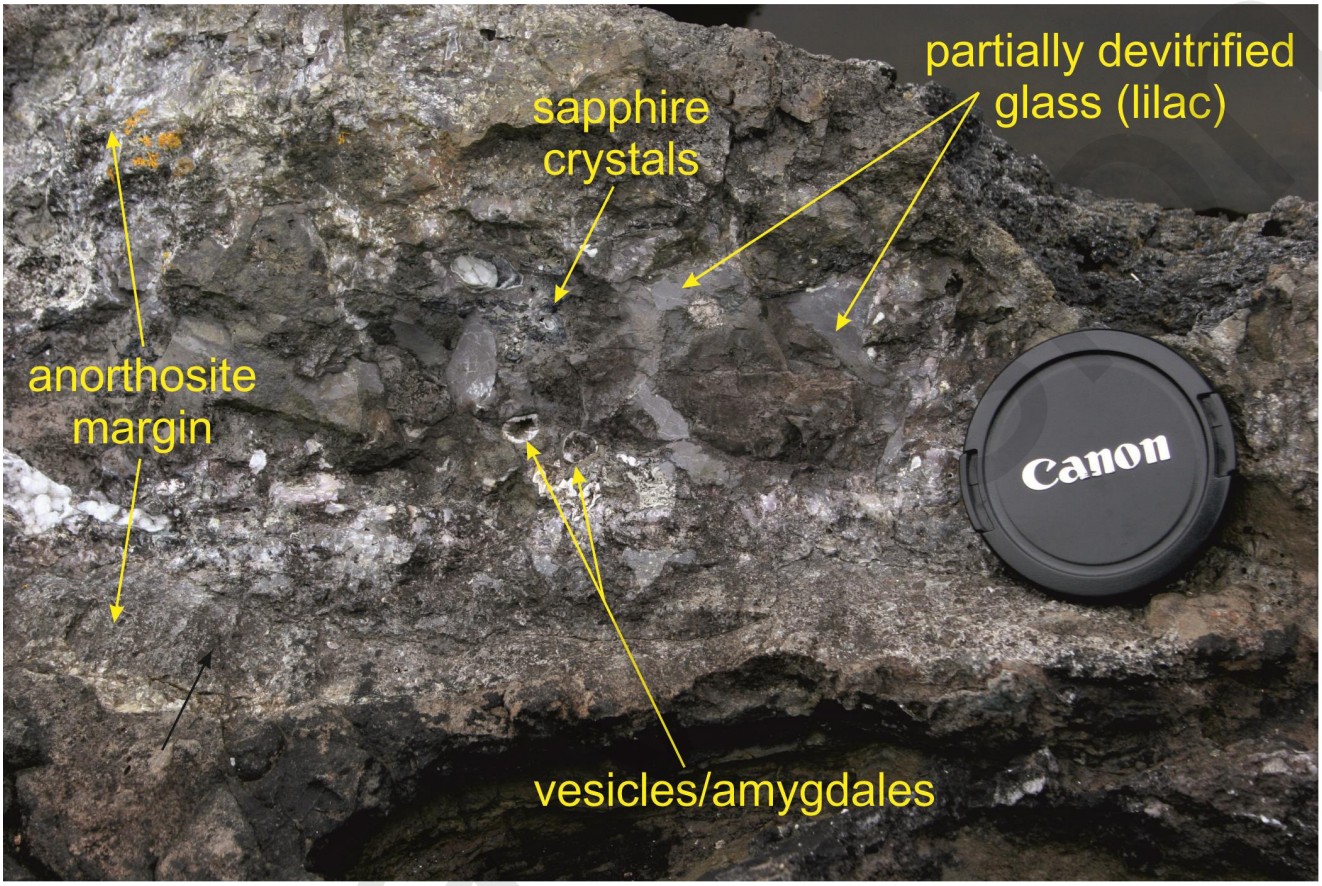


Figure 14-43: Mullite buchite (melted xenolith/inclusion) with small, poor quality sapphire crystals, Killunaig, Loch Scridain, SW Mull.

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Figure 14-44: A mineral separate of sapphires from the Rubha a' Chromain Sill, south coast of Brolass [Photograph courtesy of John Faithfull]

However, the most significant find was made in 1992 at Loch Roag, Isle of Lewis, where large sapphires, some of gem quality and accompanied by corundum and zircon, were recovered from a lamprophyre dyke (Chapter 7). An uncut, blue sapphire from this source was sold for several thousand pounds, the highest price paid for a gemstone originating in the British Isles (Figure 14-45).

Beta version



Figure 14-45: Loch Roag sapphire (photograph © Hunterian Museum & Art Gallery, University of Glasgow).

Bloodstone (a form of green jasper (cryptocrystalline silica) flecked with inclusions of red hematite) recovered from lavas in NW Rum has been used for ornamental purposes (and for 'weapons' by early Man) and small, banded agates have been obtained from the same source.

14.6 Building stone

Up to the beginning of the 20th century, local stone was employed extensively in houses and public buildings. Many examples remain, commonly roofed with Dalradian slate from Ballachulish and Easdale in Argyll. With improved transport, brick and stone from the Scottish Mainland and slate from Wales came to dominate the market, giving way in recent years to concrete blocks, which are brought in from as far afield as Antrim (where the aggregate used is local basalt), and to ceramic tiles for roofing.

The only major granite quarries are those in the attractive pink porphyritic Caledonian granite of the Ross of Mull (Faithfull 1995). The granite yields large blocks and takes a fine polish. It was quarried extensively in the 19th Century, and sporadically since; quarried stone was generally sent for polishing to Aberdeen, Glasgow or Shap in Cumbria (Figure 14-46).

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Figure 14-46: Annotated oblique Google Earth® image and field views of the Tòrr Mòr (Tormore) Quarry on the Ross of Mull, north of Fionnphort, SW Mull.

It has been used locally in Iona Cathedral, together with flagstones of Moine strata from the Ross of Mull, and in many buildings on the Ross of Mull. Elsewhere, it has been used widely, for example in the

Beta version

construction of the Liverpool docks, in several Scottish lighthouses including Skerryvore and Ardnamurchan Point (Figure 14-47; Figure 14-48), and in London it may be found in Blackfriars and Westminster bridges and the foundations of the Albert Memorial; it was also exported to New York and other places in North America. Production largely ceased before the First World War (1914-18) but, since 1985, previously quarried blocks have been removed from the Tormore quarries and some new stone has also been won.



Figure 14-47: Ardnamurchan lighthouse, built from granite from quarries on the Ross of Mull, north of Fionnphort, SW Mull.

Beta version



Figure 14-48: Ardnamurchan lighthouse, built from granite from quarries on the Ross of Mull, north of Fionnphort, SW Mull.

Despite an abundance of Paleocene granites, the only granitic rock of this age to have been quarried extensively is the distinctive blue-grey, riebeckite-bearing microgranite of Ailsa Craig (Figure 14-49; Figure 14-50; Figure 14-51; Figure 14-52; Figure 14-53; Figure 14-54). This was used for paving sets, in Glasgow and elsewhere, and as an ornamental stone, as in the floor of the Scottish National War Memorial, Edinburgh Castle. However, it is best-known for the curling stones that were manufactured in their thousands towards the end of the 19th Century, and continue to be produced, albeit in much smaller quantities. The roughed-out stones are finished on the Scottish Mainland, with many exported to Canada. The running surfaces for curling stones currently used in all World Championship and Olympic events are from Ailsa Craig, and the polished microgranite continues to find ornamental uses (Nichol 2001).

Beta version



Figure 14-49: Ailsa Craig, Firth of Clyde. View towards the north.



Figure 14-50: Ailsa Craig granite, used to make internationally used curling stones.



Figure 14-51: Ailsa Craig granite, used to make internationally used curling stones.



Figure 14-52: Ailsa Craig granite, used to make internationally used curling stones.

Below



Figure 14-53: Ailsa Craig granite, used to make internationally used curling stones. Coin ca. 24 mm across.



Figure 14-54: Redundant tramway at Ailsa Craig granite quarry.

Very large amounts of excellent building stone have been obtained from the Carboniferous and New Red Sandstone strata of Arran. White freestone from the Lower Carboniferous at Corrie was used extensively in the late 18th and 19th centuries, for example in the construction of the Crinan Canal, but the most extensive exploitation was of the red-brown rocks of the New Red Sandstone (Figure 14-55). In addition to local use, the Lower Permian Corrie Sandstone was employed in many works outside Arran, for example at Troon Harbour and Kinloch Castle on Rum (Figure 14-56).



Figure 14-55: Abandoned sandstone (New Red Sandstone) quarry, Corrie, NE Arran. In southern Arran, the red sandstones on the south side of Lamlash Bay, at Cordon and Monamore Mill, were extensively quarried.



Figure 14-56: Kinloch Castle, Rum.

Triassic sandstones in Morvern and elsewhere have been quarried for local building use, and around Broadford, Skye, the local Lower Jurassic rocks provided freestone suitable for building. The quartz porphyry and dolerite sills in the south of Arran have also been used locally.

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14.7 Aggregate

Small roadside quarries are still used as sources of aggregate on several of the islands, particularly in the Small Isles where shipment facilities were poor until recently. Basalt rubble is applied to the tracks on Muck, Eigg and Canna, although in the past marble chips, most likely obtained from Skye, were used to surface the tarred roads on Eigg and Muck.

On Skye, the large, well-equipped quarry in Torridonian sandstone at Peinchorran, near Sconser (Figure 14-57; Figure 14-58; Figure 14-59), provides road aggregate for the island, although hornfelsed lava from a quarry near Sligachan (Figure 14-60) and dolerite from a Paleocene sill at Invertote have in the recent past provided material for major road rebuilding programmes. One abandoned quarry worthy of note is located east of Ord, at Coille a' Chuaraidh (Figure 14-61) where Cambro-Ordovician sandstone ('quartzite') was quarried and the aggregate was transported downhill to a slipway at Ord using a hand-worked narrow gauge rail system . Remnants of the infrastructure are still to be found in the immediate area, including where pieces of rail are used as fence posts. Production started in 1945 and ended in 1960.



Figure 14-57: Aggregate (hornfelsed Torridonian Supergroup sandstone) quarry at Peinchorran, east of Sconser, Skye.



Figure 14-58: Detail of aggregate (hornfelsed Torridonian Supergroup sandstone) quarry at Peinchorran, east of Sconser, Skye.

Beta version



Figure 14-59: Detail of aggregate (hornfelsed Torridonian Supergroup sandstone) quarry at Peinchorran, east of Sconser, Skye.



Figure 14-60: Oblique Google Earth® image and field view of the (abandoned) aggregate (hornfelsed Paleocene basaltic lavas and dykes) quarry, NE of Sligachan, Skye.

Better version



Figure 14-61: Abandoned aggregate (recrystallised Cambrian sandstones ('quartzite') quarry, Coille a' Chuaraidh, east of Ord, Sleat, SE Skye.

On Mull, altered basalt from within the limit of pneumatolysis around the central complex is used as roadstone and is obtained from a quarry near Salen. Aggregate has also been obtained from a basalt quarry east of Bunessan and from a quarry in a granite ring-dyke south of Salen.

On Arran, roadstone has been imported since the 1920s (Tyrrell 1928). However, a quarry in felsite at Bennecarrigan in SW Arran produces aggregate for roads and also some building stone. At Dereneneach, on the western margin of the Central Arran Ring-complex, a quarry in granite supplies aggregate for local use (Figure 14-62; Figure 14-63; Figure 14-64).

Beta version



Figure 14-62: Aggregate (Paleocene felsite/microgranite) quarry, Dereneneach on The String Road, (Shiskine-Brodick), Arran.



Figure 14-63: Detail of aggregate (Paleocene felsite/microgranite) quarry, Dereneneach on The String Road, (Shiskine-Brodick), Arran.

Preview



Figure 14-64: Detail of aggregate (Paleocene felsite/microgranite) quarry, Dereneneach on The String Road, (Shiskine-Brodick), Arran.

No large coastal quarries are projected for the district, although the granite of western Rum has been identified on geological grounds as a possible site. However, the exposed coast and the National Nature Reserve status of the island make its exploitation improbable.

14.8 Sand and gravel

Large amounts of sand and gravel are extracted from quarries in thick (over 10 m) gravel deposits on marine raised beaches at Allt Anavig and Lusa, west of Kyleakin (Figure 14-65; Figure 14-66; Figure 14-67), Skye, and local use has been made of the gravel deposits at the mouth of the River Brittle, Skye.

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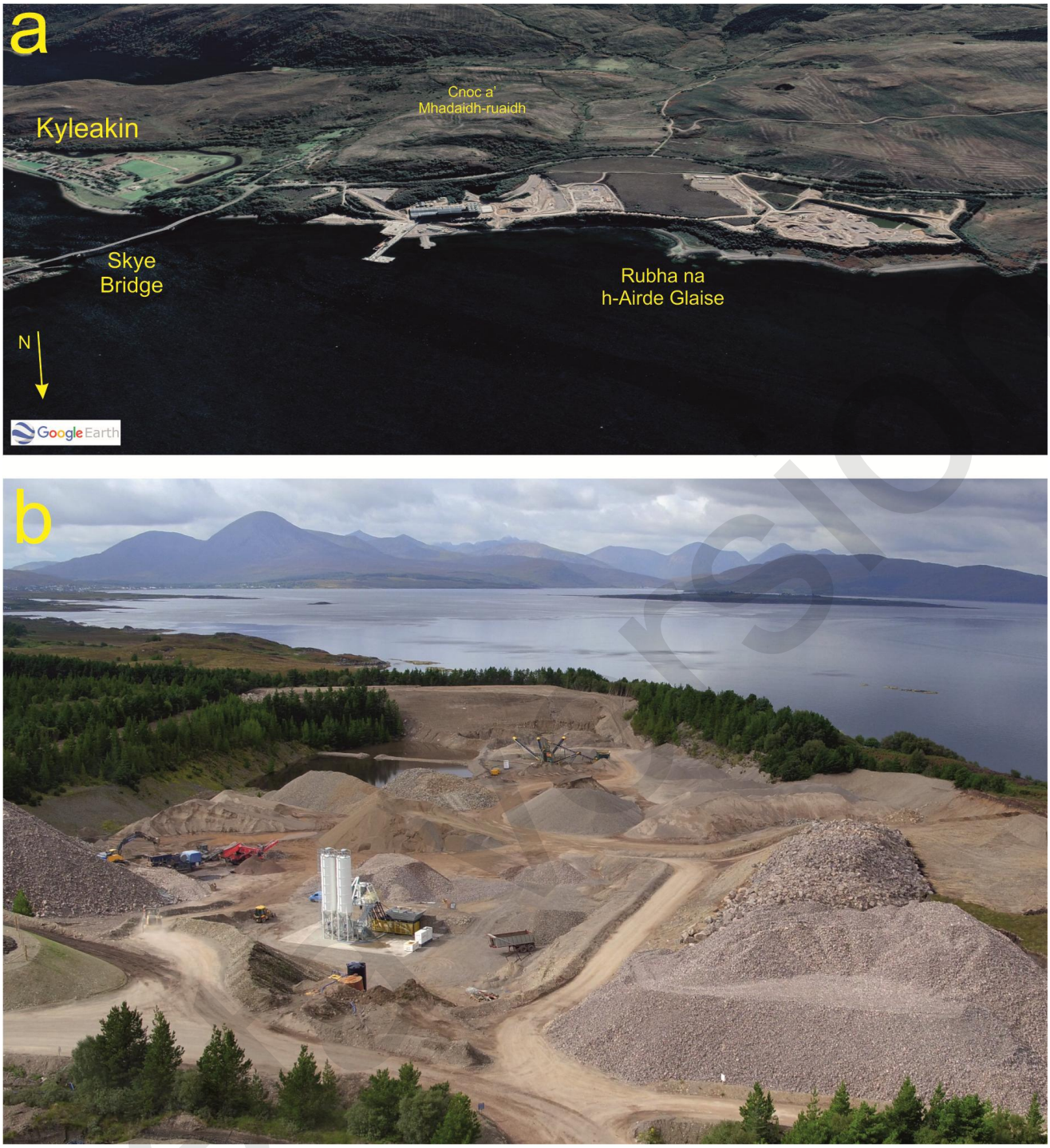


Figure 14-65: Annotated oblique Google Earth® image and field view of the aggregate (raised beach) quarry, Rubha na h-Àirde Glaise on the north side of the Broadford – Kyleakin Road (A87), Skye.

Be



Figure 14-66: Raised beach aggregate deposit in (raised beach) quarry, Rubha na h-Àirde Glaise on the north side of the Broadford – Kyleakin Road (A87), Skye.



Figure 14-67: Raised beach aggregate deposit in (raised beach) quarry, Rubha na h-Àirde Glaise on the north side of the Broadford – Kyleakin Road (A87), Skye.

On Mull, the extensive moraines north of Loch Don are a source of sand and gravel. Silica-rich beach sands are used locally in Ardnamurchan, Skye and Mull as sharp sand in cement and concrete; on Arran, sand from glacial outwash deposits near Brodick Castle was exported for building purposes.

Draft version

14.9 Silica sandstone and silica (‘glass’) sand

At Loch Aline, on Morvern, a deposit of white sandstone of exceptionally high purity (99.7% quartz and generally 0.01% Fe_2O_3 or less) is worked as a source of sand for glass manufacture (Figure 14-68; Figure 14-69; Figure 14-70). The sand is mined from a bed of Cretaceous sandstone that averages 12 m in thickness (of which approximately 5 m are worked), underlying the Paleocene lavas. Although the deposit has been known since the end of the 19th Century, the mine was only opened in the 1940s when other European sources of pure sand were cut off during the Second World War. Currently, production is about 120,000 tonnes per year. The deposit is the only United Kingdom source of sand suitable for high-grade domestic, scientific and commercial glass. The sand is crushed at the mine and all is shipped out. About 50% of the production is currently exported, principally to the Republic of Ireland and to Scandinavia where cheap hydroelectricity makes it economic to mix the sand with graphite in the manufacture of 'carborundum' (silicon carbide) abrasive.



Figure 14-68: Closed/abandoned entrance to the Lochaline (white) sandstone mine on the west side of Loch Aline, Morvern.



Figure 14-69: Stockpiled, crushed white sandstone from the Lochaline glass-sand mine on the west side of Loch Aline, Morvern.



Figure 14-70: Quartz sand stockpiled at the Lochaline glass-sand mine on the west side of Loch Aline, Morvern.Limestone and dolostone.

The principal carbonate rocks of the district are in the Cambro-Ordovician Durness Group on Skye, the Carboniferous succession of Arran, and the Mesozoic sequences throughout the Inner Hebrides. Durness

Group dolostones are recrystallised to marble adjacent to the Paleocene granites of the Eastern Red Hills Centre and the Broadford Gabbro, Skye. The marble, which includes brucite- and serpentine-rich varieties, was formerly quarried extensively in the roof zone of the Beinn an Dubhaich Granite for ornamental stone slabs and as chips for terrazzo flooring. A tramway was constructed to take products from Strath to Broadford, from where they were shipped. The quarries are long abandoned but nearby, at Torrin, the Skye Marble Company produces up to 20,000 tonnes per year of crushed chips, used principally for harling and for roadstone.

14.9.1 Strath Marble Quarries

Some of the earliest observations that marble was extracted from the thermally altered Cambro-Ordovician Durness Group dolostones in Strath were made by Martin Martin (*A Description of the Western Isles of Scotland,* 1716), Thomas Pennant (*A Tour in Scotland, and Voyage to the Hebrides,* 1772) and John Macculloch (*A Description of the Western Isles of Scotland, Including the Isle of Man,* 1819). Macculloch (1819) noted that material was exported from Skye as an ornamental stone, with its attractive patches of green coloration due to hydration of metamorphic olivine to serpentine.

In the first decade of the 20th Century, an extraction company was set up and started to work material that occurs adjacent to gabbro 2.5 km NW of Broadford. A short tramway was built to enable material to be transported to the public road and onwards to a pier on the west side of Broadford Bay. Peach *et al.* (1910) record that in 1908 the only material exported from this venture was small chips of marble for the production of mosaic cubes and terrazzo mosaic. It was planned to develop slab and block production thereafter. There are no records as to how this developed but it is safe to say that it was not successful, and the operation was terminated.

The same company set up trial quarries SE of Loch Cill Chriosd (Kilchrist), which were subsequently expanded and produced substantial blocks of ornamental stone for export (Figure 14-71; Figure 14-72; Figure 14-73; Figure 14-74; Figure 14-75). It is recorded that blocks and slabs of this marble were used in buildings such as Iona Abbey and Armadale Castle, the latter on the Sleat Peninsula, SE Skye.

The enterprise started in 1907 with an on-site processing plant close to Loch Cill Chriosd for cutting and polishing material. Subsequently, production extended to crushed stone (aggregate) that was then transported 3 miles (5km) to the pier at Broadford on a narrow gauge (914mm or 3 feet) railway. Horses initial provided the pulling power but were replaced briefly by steam power. The locomotive used, *Skylark,* was built in 1892 by the Hunslet Engine Company of Leeds. The operation closed in 1912. The infrastructure of the operation (houses, a shop and a club) were demolished, the railway line was lifted and the train disposed of. The locations of the upper and lower railway lines are still visible, the upper marked by the so-called Marble Line Path (part of the path between Broadford to Boreraig). Still preserved on-site items of interest include remnants of some buildings, including a crushing plant, the railway loading platform, and the base of a wagon turntable. The railhead at Broadford was located close to the outflow of the Broadford River.

Beta version



Figure 14-71: Typical marble from one of the abandoned quarries at Kilchrist, Strath. The green coloration is metamorphic olivine replaced by secondary serpentine. Coin c. 24mm across.



Figure 14-72: Information board with details of the early 20th Century marble quarries at Kilchrist, Strath.

Beta version



Figure 14-73: Workers at the Kilchrist marble quarries, Strath.



Figure 14-74: The steam locomotive Skylark, used to haul material from the Kilchrist quarries to the pier at Broadford.

Preview



Figure 14-75: Loading marble at the old pier at Broadford, at the end of the rail line from the Strath marble quarries, Kilchrist, Strath.

Interest in the marble as a slow-release fertiliser and aggregate was rekindled after the Second World War and, in 1951, a small quarry, now abandoned, was developed at Cnoc Slapin (Figure 14-76; Figure 14-77). Production switched to the active quarry in Torrin in 1960 (Figure 14-78; Figure 14-79). Currently, the range of products comprises slow-release fertiliser, concrete products, decorative stone and pebble dash coatings for buildings.

Beta version



Figure 14-76: The abandoned marble quarry at Cnoc Slapin, Strath, close to the head of Loch Slapin. View towards the NE from the east side of Strathaird.



Figure 14-77: Detail of the abandoned quarry at Cnoc Slapin, Strath, with a segmented Paleocene dolerite dyke within Cambro-Ordovician Durness Group dolostones. Fence post for scale.



Figure 14-78: The active marble quarry at Torrin, Strath. Views from above Kilbride and from the Kilbride-Camas Malag Road.



Figure 14-79: Detail of the active quarry at Torrin, Strath, with irregular-shaped Paleocene dolerite dykes within Cambro-Ordovician Durness Group dolostones.

Browser version

14.9.2 Corrie Carboniferous limestones

The Lower Carboniferous Corrie Limestone in eastern Arran was extensively quarried and mined for lime, mainly to improve the soil for agriculture. Remains of the lime kilns are still visible (Figure 14-80; Figure 14-81; Figure 14-82).



Figure 14-80: Caves excavated during removal of limestone for agricultural use, Corrie, NE Arran.



Figure 14-81: Exposure of the Lower Carboniferous limestone put to agricultural use, Corrie, NE Arran.



Figure 14-82: Remains of kiln constructed at Corrie, NE Arran, to calcine (heat treat) Lower Carboniferous limestone for agricultural use.

14.9.3 Other limestones

Calcining for agricultural lime has been the principal use for Mesozoic limestones and the ruins of small lime kilns occur near many of the main outcrops, for example where Lias limestone crops out at Broadford, Skye and at Mingary and Swordle on Ardnamurchan. The Middle Jurassic limestones of the Duntulm and Kilmaluag formations of Skye and Eigg were calcined locally.

Marble was obtained from a lens within the Lewisian of Iona (Figure 14-83) (see Johnstone & Mykura 1989).



Figure 14-83: Abandoned marble quarry, SE Iona.

Shelly beach sands and the so-called 'coral sands' with a high calcium carbonate content occur in many places on the coast but have been little used apart from local exploitation for agricultural lime.

14.10 Coal

In the 18th Century, there was a small working for coal in the Carboniferous rocks south of the Cock of Arran, where seams *ca*. 1 m thick were reported (Tyrrell 1928). Coal Measures crop out at Inninmore, Morvern, but do not contain any workable coal seams in the exposed 60 m of section. In northern Skye, lignitic coals occur in thin seams in the Great Estuarine Group, where they pass laterally into oil shale; locally, this poor-quality coal was used as fuel. Thin seams and streaks of poor-quality coal between Paleocene lavas occur sparsely throughout the district, for example close to the base of the lava sequence near Portree, Skye, in tuffs to the east of Fionchra, Rum, and at Carsaig and Malcolm's Point on the south coast of the Ross of Mull. Lignites associated with the lavas of Ardtun, Mull, were investigated for the Duke of Argyll, but were found to have high ash and moisture contents. Similar lignitic coal was reported in a seam *ca*. 60 cm thick at Ardslignish, Ardnamurchan.

Beta version

14.11 Graphite

An unworked seam of graphite was reported from Mesozoic strata on the north side of Loch Sligachan, Skye (Peach *et al.* 1910). Graphite also occurs in small blocks in the Paleocene Loch Scridain sills, Mull (Chapter 8), where attempts were made to extract it in the 19th Century. Jet (a type of lignite, a mineraloid, with a variety of uses) has been reported from the Jurassic sedimentary rocks of Holm, north Skye and from sedimentary rocks underlying basalt lavas on Ben Hiant, Ardnamurchan.

14.12 Oil

Although there is considerable interest in the oil-bearing potential of the Mesozoic and Paleocene sedimentary sequences off the west and NWt coast of Scotland, onshore possibilities are limited. However, there has been some exploratory drilling on Skye. In the north of Skye and the south of Raasay, oil-shale up to 3 m thick occurs in the Great Estuarine Group. The oil potential of these rocks has been compared favourably with that of the Carboniferous oil-shales in the Lothians, with up to 54 litres of crude oil per tonne of shale obtained in tests (Anderson & Dunham 1966).

14.13 Peat

This was the principal fuel throughout the Scottish Highlands and Islands until well into the 20th Century (Figure 14-84). It was gradually replaced by coal from the Midland Valley of Scotland, and more recently by oil and bottled gas. Small workings continue to the present, notably in northern Skye where considerable areas of blanket bog peat exist, up to 3 m thick in places (Figure 14-85). Nowhere has machinery been employed to win peat commercially.

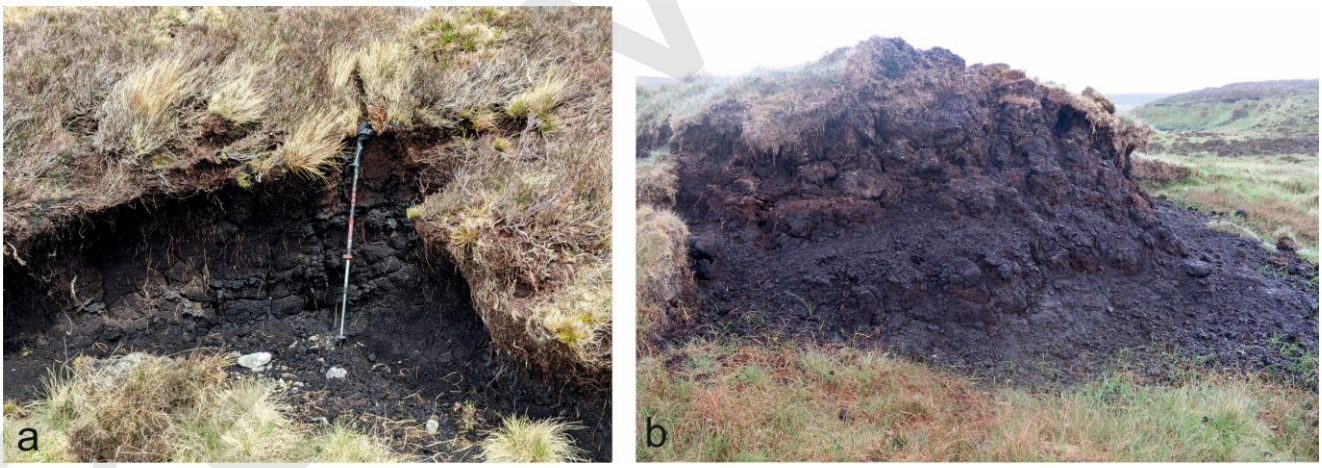


Figure 14-84: Exposed banks of peat between the Lealt River and the dismantled railway that accessed Loch Cuithir (for diatomite) below the Trotternish Escarpment, WSW of Lealt. Pole *ca*. 1 m long.

Beta version



Figure 14-85: Active peat cut, Suishnish, Strath, Skye.

14.14 Water supply

A small hydroelectric station on the Bearreraig River, Skye, makes use of the fall at sea cliffs near the outlet from Loch Leathan, north of Portree (Figure 14-86; Figure 14-87; Figure 14-88; Figure 14-89; Figure 14-90; Figure 14-91; Figure 14-92). The installation contributes power to National Grid. The drop in water height of *ca.* 136 m enables *ca.* 2.4 MW of electricity to be produced from new turbines that were installed in 2017. The infrastructure was constructed in the early 1950s and started generating electricity on 31st May 1952.

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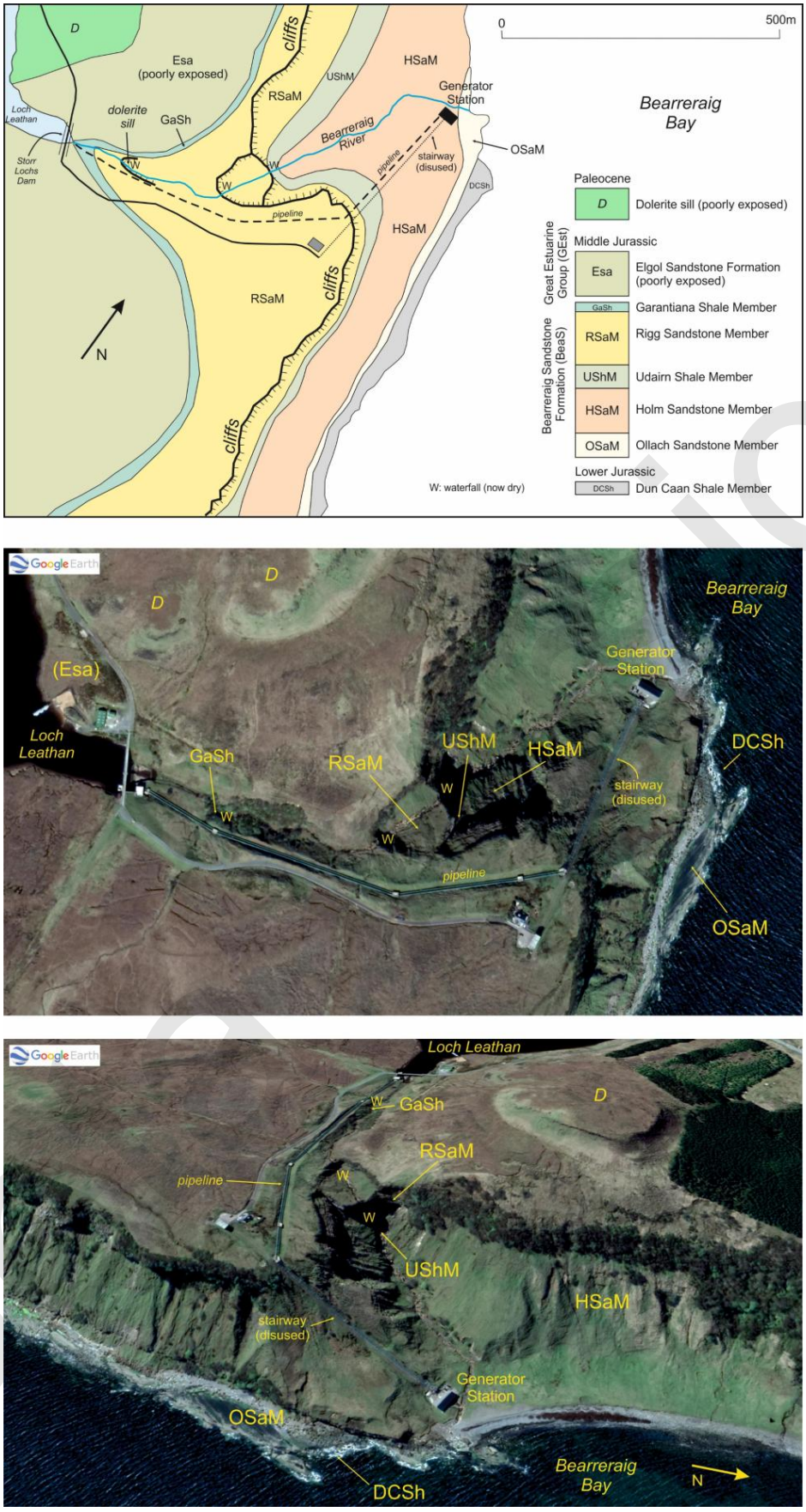


Figure 14-86: Summary geological map, key and annotated Google Earth® images of Bearreraig Bay, Trotternish, Skye, including details of the hydroelectric scheme.

Consultation



Figure 14-87: The Storr Lochs from The Storr, Trotternish, Skye.



Figure 14-88: Storr Lochs dam/viaduct, Trotternish, Skye.



Figure 14-89: Storr Lochs dam/viaduct, Trotternish, Skye.



Figure 14-90: Twin pipes of the Storr Lochs hydroelectric scheme, Trotternish, Skye.



Figure 14-91: Twin pipes of the Storr Lochs hydroelectric scheme, Trotternish, Skye.



Figure 14-92: Generator house of the Storr Lochs hydroelectric scheme, Trotternish, Skye.

There are local hydroelectric schemes, for example on Rum, which has supplied Kinloch Castle since the early 20th century, and on Eigg.

The small communities scattered throughout the region rely extensively on surface water for supplies, which renders them vulnerable to drought and, less commonly, to frost. Water obtained from burns and wells is commonly piped short distances to isolated houses. The larger settlements are generally supplied from small reservoirs and from lochs in nearby hills. The largest groundwater system is on Arran where several boreholes into the Permian sandstones in the Brodick - Lamlash Bay area and in the Shiskine valley serve the southern half of the island.

14.15 Diatomite

Deposits of diatomite are common in the small lochs and hollows amongst the landslipped lavas resting on sills and Mesozoic strata in northern Trotternish, Skye (Haldane *et al.* 1940; Anderson & Dunham 1966). Many of the occurrences have been worked on a small scale, but the Loch Cuithir deposit, at over 6 m, was the thickest, and was worked up to 1914; the diatomite was transported to the coast at Invertote by a 5 km-long tramway. It was formerly used in the manufacture of dynamite, but later the principal uses were as a filter and as an insulator. Thin diatomite deposits near Loch Bà, Mull have been used locally for whitewash.

Diatomite was discovered at a number of locations on Trotternish in north Skye in 1886 and exploited by the Skye Diatomite Company from 1899.

Diatomite (diatomaceous earth, or *kieselguhr*) is the remains of diatoms, single-celled aquatic algae made of opaline silica that can accumulate in fresh-water loch (lake) sediments. If no other material is deposited, very pure layers can form. It is green when wet and white when dry and processed. Diatomite is capable of absorbing up to three times its weight of water. Consequently, after processing, it has a wide variety of commercial applications: a stabiliser for explosives; filters; very mild abrasives; insecticides; thermal barriers; and various agricultural products.

Discoveries were made at at Digg, Sartle and Kilmuir, with the most extensive being at Loch Cuithir, below Flasvein on the inland lava escarpment (Figure 14-93; Figure 14-94; Figure 14-95; Figure 14-96; Figure 14-97; Figure 14-98). The deposits accumulated on Quaternary glacial moraines during the Holocene Epoch, a period of relatively higher temperatures; however, the presence of overlying peat, which has formed during subsequent less mild and wetter conditions, suggests that diatomite is no longer accumulating.

All that is left of this industry that employed up to fifty people at Loch Cuithir are remnants of the narrow gauge (2 foot; 61cm) tramway that ran parallel to the Lealt River, and derelict buildings at Loch Cuithir and at Inver Tote on the coastline. The diatomite was processed at Inver Tote and shipped out. Peat was cut during the winter months to facilitate the kiln drying process.

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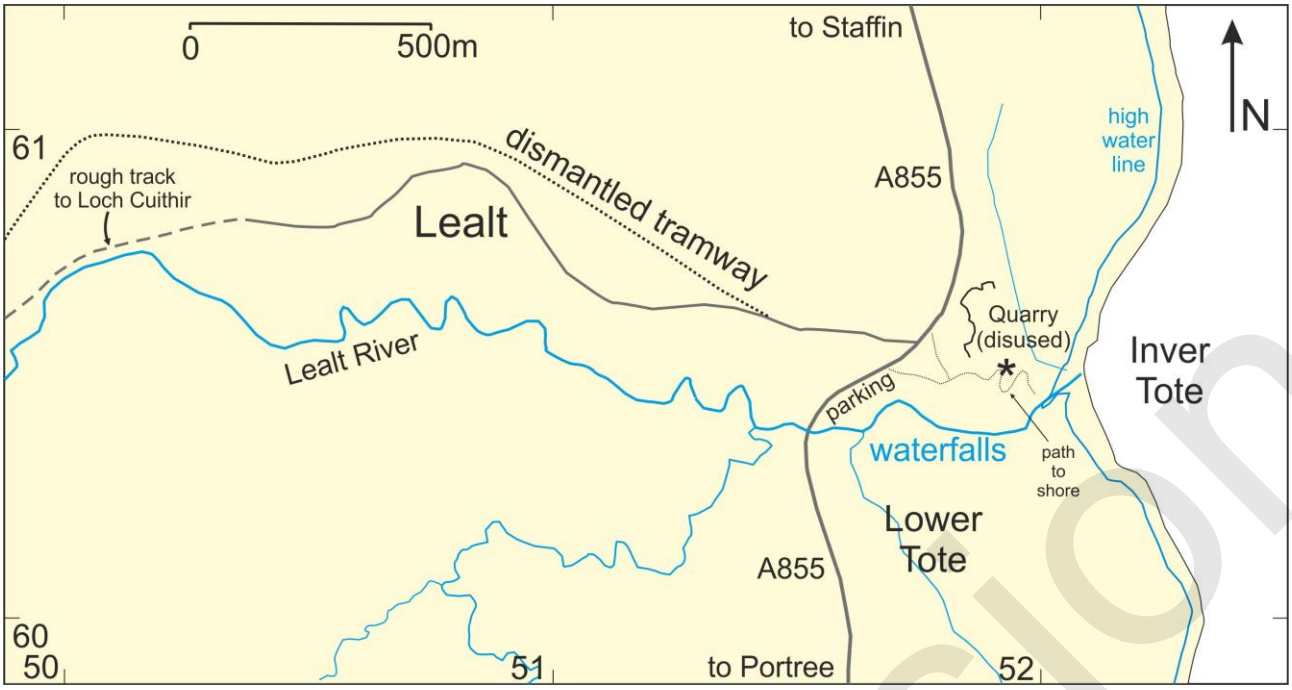


Figure 14-93: Location map for Loch Cuithir - Lealt - Inver Tote area, Trotternish, Skye.



Figure 14-94: Information board on the Loch Cuithir diatomite exploitation at the Lealt River coastal viewpoint, Trotternish, Skye.

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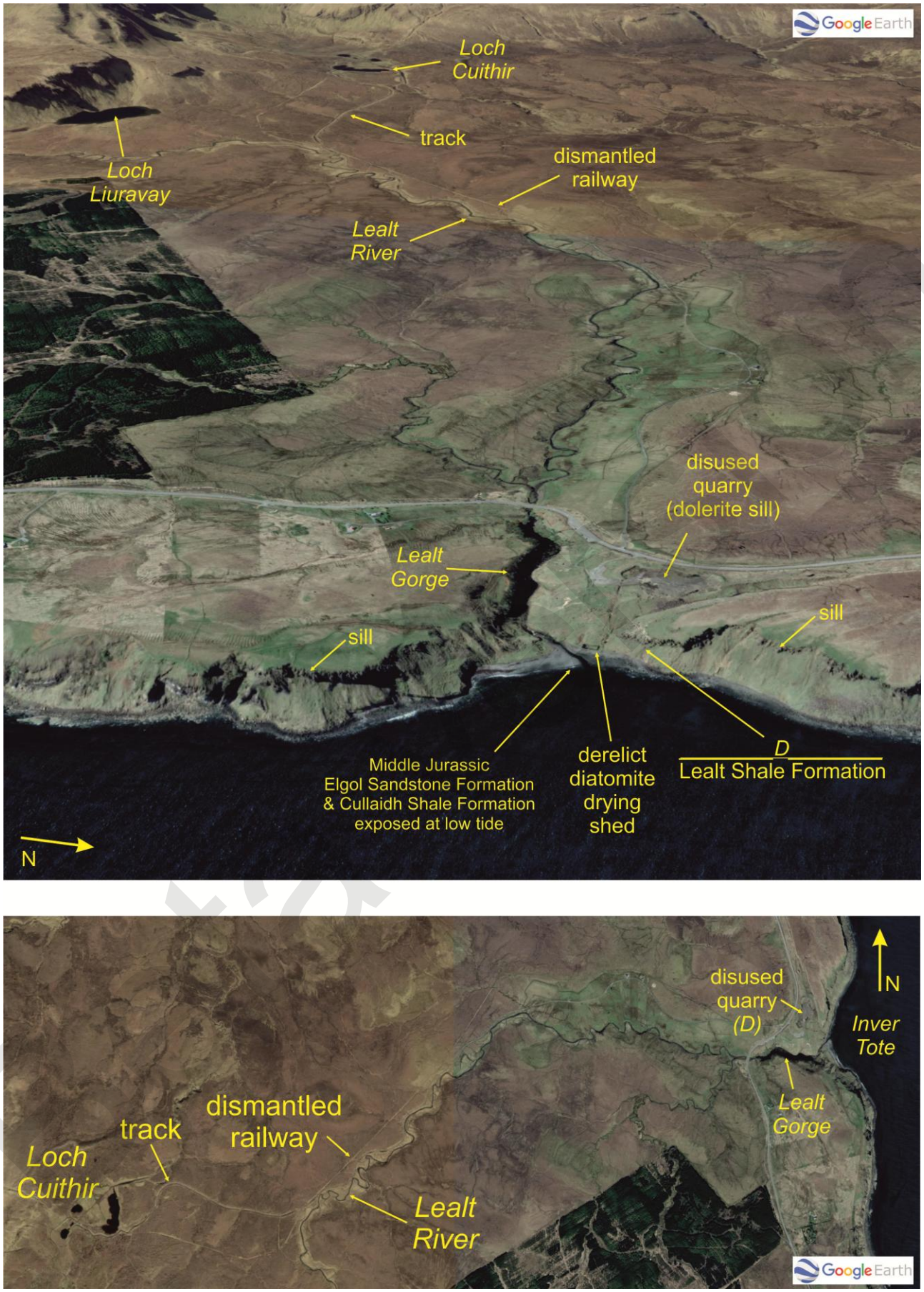


Figure 14-95: Annotated Google Earth® images of the Loch Cuithir – Inver Tote area, Trotternish, Skye.



Figure 14-96: Loch Cuithir, Trotternish, Skye, view towards the west.



Figure 14-97: Remains of extraction plant at Loch Cuithir, Trotternish, Skye.

Draft version



Figure 14-98: Trace of tramway between Loch Cuithir and Inver Tote, Trotternish, Skye. View towards the west.

Locally known as *caile* (Gaelic, chalk), the diatomite was dried on wire nets at Loch Cuithir and then transported to Inver Tote, initially on horseback, but subsequently via a gravity-driven tramway, first by manpower and later using a stream locomotive. At Inver Tote, the diatomite was kiln dried, ground and calcined (heat treated, to remove carbonate and any organic material) (Figure 14-99). It is estimated that *ca*. 2000 tons of diatomite were extracted.



Figure 14-99: Remains of the kiln at Inver Tote, Trotternish, Skye.

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The diatomite from the Loch Cuithir deposit is very pure, with little or no interlayered silt or mud, and contains over 96% silica (SiO_2). The absorptive value of the material is over 3.56 (a good diatomite would have an absorptive value in excess of 4.0).

An article in *The Scotsman* newspaper, published in 1887, describes the construction of the extraction and processing infrastructure. It also describes how the loch was drained via the formation of a 300m long cutting, 4m wide and 4m deep.

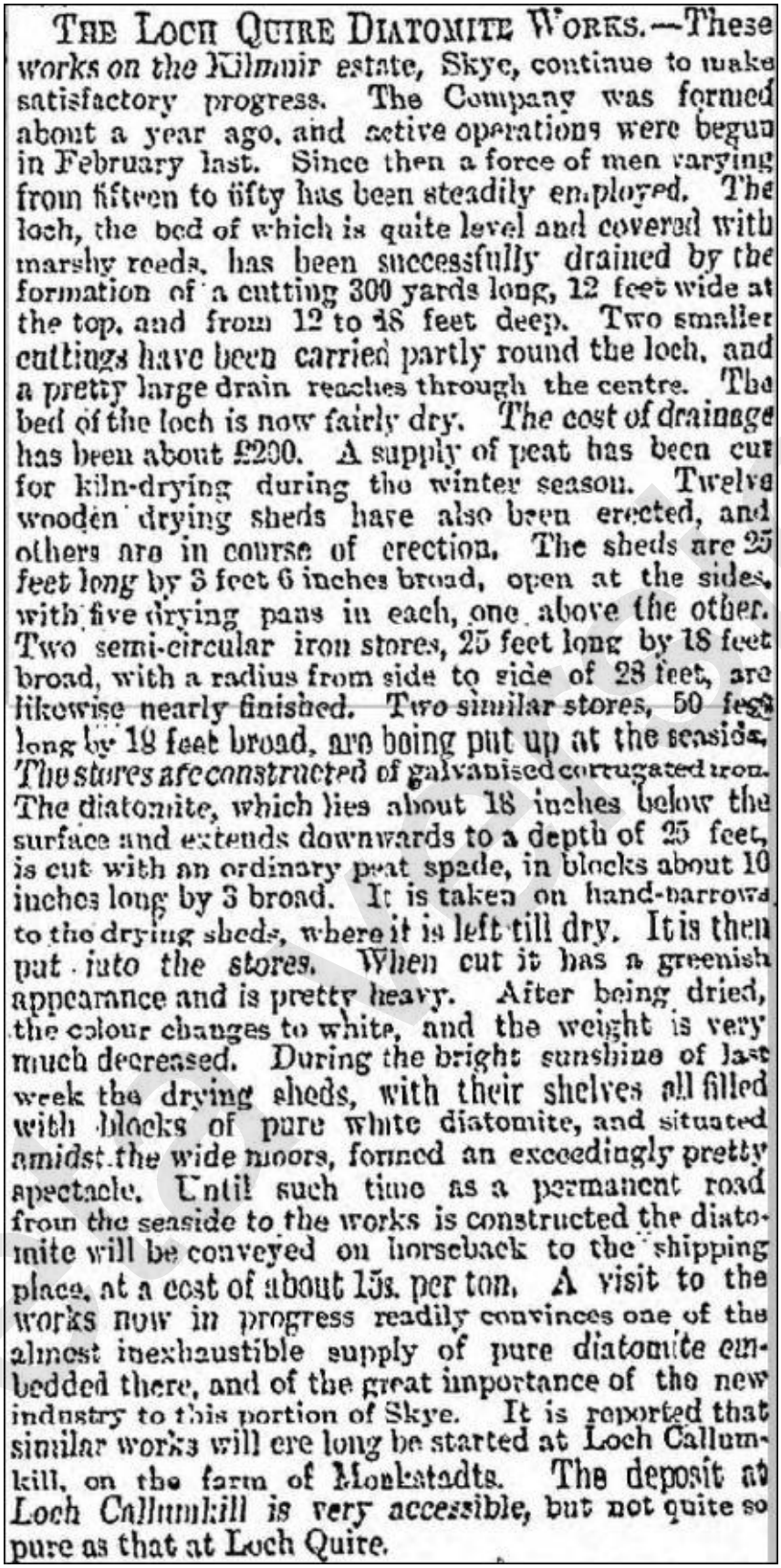
The diatomite formed a layer just 0.5m below the surface, extending to a depth of *c.* 8m, and was cut using a peat spade into blocks and hand-barrowed to the drying sheds.

One account of the activity was recorded by Dr J. A. MacCulloch, Rector of Saint Columba's in Portree. His report was compiled from observations made on one of the boats that collected the diatomite:

'A drying and grinding factory has been erected at the water's edge; great sheds stand on the upper slopes at a precarious angle; while a miniature railway, a continuation of one which runs inland to the diatomite beds, connects the edge of the cliff with the landing-stage and factory far below. When we arrived the work-people were all at the loch and there was scarce a sign of life round this lonely day. But presently a long train of men and women began to zigzag down the path on the face of the slope and transformed this solitude into humming activity. They must get the cargo embarked while the tide served. Each one carried a bag of diatomite from the grinding-house to the boat slip, till the coble was piled up with sacks. Then it made a slow journey to the steamer, where the sacks were transferred to the hold. Meanwhile a second coble was a-filling, and so all day long, for there were hundreds and hundreds of sacks to be removed, the work went steadily on.'

An article in *Scotsman* newspaper describes how the diatomite was processed (Figure 14-100).

Beta version



THE LOCH QUIRE DIATOMITE WORKS.—These works on the Kilmnir estate, Skye, continue to make satisfactory progress. The Company was formed about a year ago, and active operations were begun in February last. Since then a force of men varying from fifteen to fifty has been steadily employed. The loch, the bed of which is quite level and covered with marshy reeds, has been successfully drained by the formation of a cutting 300 yards long, 12 feet wide at the top, and from 12 to 18 feet deep. Two smaller cuttings have been carried partly round the loch, and a pretty large drain reaches through the centre. The bed of the loch is now fairly dry. The cost of drainage has been about £200. A supply of peat has been cut for kiln-drying during the winter season. Twelve wooden drying sheds have also been erected, and others are in course of erection. The sheds are 25 feet long by 3 feet 6 inches broad, open at the sides, with five drying pans in each, one above the other. Two semi-circular iron stores, 25 feet long by 18 feet broad, with a radius from side to side of 23 feet, are likewise nearly finished. Two similar stores, 50 feet long by 18 feet broad, are being put up at the seaside. The stores are constructed of galvanised corrugated iron. The diatomite, which lies about 18 inches below the surface and extends downwards to a depth of 25 feet, is cut with an ordinary peat spade, in blocks about 10 inches long by 3 broad. It is taken on hand-barrows to the drying sheds, where it is left till dry. It is then put into the stores. When cut it has a greenish appearance and is pretty heavy. After being dried, the colour changes to white, and the weight is very much decreased. During the bright sunshine of last week the drying sheds, with their shelves all filled with blocks of pure white diatomite, and situated amidst the wide moors, formed an exceedingly pretty spectacle. Until such time as a permanent road from the seaside to the works is constructed the diatomite will be conveyed on horseback to the shipping place, at a cost of about 15s. per ton. A visit to the works now in progress readily convinces one of the almost inexhaustible supply of pure diatomite embedded there, and of the great importance of the new industry to this portion of Skye. It is reported that similar works will ere long be started at Loch Callumkill, on the farm of Monkstadts. The deposit at Loch Callumkill is very accessible, but not quite so pure as that at Loch Quire.

Figure 14-100: Details of how diatomite from the Loch Cuithir deposit was processed (from the Scotsman (23rd June 1887)).

Production was significant during the First World War and intermittent thereafter. Production finally ceased in 1960. A feasibility studied at the end of the 1960s concluded that a restart to extraction was uneconomic. A useful summary was published in the *Stornoway Gazette* (5th March 2008):

In the Trotternish area of Skye, taking the Staffin Road out of Portree, travellers will pass the Storr Rock, and then after continuing a further five miles or so, arrive at a lay-by near a gorge with a sign pointing off to the left, indicating the small community of Lealt. There is a lot more to this area than first meets the eye, and it's all down to a substance called Diatomite and even a brush with German espionage. Known to the locals as 'Caile' (Gaelic for chalk), Diatomite is a clay-like floury grey substance, found in certain freshwater lochs and suppling many minerals used in the production of numerous products, ranging from beverages, sugars and cosmetics to chemicals, industrial oils and paint. Trotternish was home to two mining areas – one in Digg, Staffin, and the other at Loch Cuithir in Lealt. Although little is known of the Digg mine, where production ended sometime after the First World War, it is the history of the Loch Cuithir mine which is of interest. Work began at Cuithir in 1899 and finally ceased over six decades later in 1960. Over the years, the mine saw periods of inactivity, but when up and running operations made use of the large industrial works at the area – a large factory building, a railway with embankment cuttings, and a rolling stock traversing three miles of landscape, including an aerial ropeway. The light railway was used to transport the Loch Cuithir Diatomite to the shores at Invertote for a final drying and grinding, and a large building containing a furnace, grinding machine and storage space was constructed there for this purpose. Such modernised business works were quite remarkable for this part of the world at the time. In those days there was no road between Staffin and Portree, so a puffer boat would anchor in the bay at Lealt, and local skiffs were used to transport the finished Diatomite from shore to boat, ready for shipping to the mainland. There were around 40 to 50 people steadily employed at Lealt, yet on days that the boat came in this total rose to as many as 80 workers. Perhaps one of the most intriguing aspects of the mine's history comes from the ownership of the drying factory at Invertote by Germans. Although closed during the period of the Great War, surprisingly the now enemy foreign residents were allowed to stay on. Shortly afterwards a rumour began to circulate that the area was haunted and that the ghost of a recent tragic death at the Lealt Falls had appeared at the factory. As the local story goes, (the rumour was actually started by the Germans) with the intent of keeping locals away. It turned out that the resident Germans were spies and that, almost unbelievable to the community, the area was being used as a German base with submarines surfacing in the sea bay! Moving on, the year 1950 saw the next development in the mining of Diatomite from Loch Cuithir. As the loch was one and a half miles up the moor, through peat bogs and rivers, the Department of Agriculture and Fisheries for Scotland (DAFS) decided that a road should be built, with the intention of extracting the Diatomite by digger, and then taking it to the Lealt road end above Invertote. The road took around a year and a half to build, during which the mine was put out of operation. Yet, when production started again, the new method of extraction did not reach the high standard of quality which was achieved when extracted manually by spades. The mechanical extraction resulted in the diatomite being less pure, and full of unwanted dirt. Drying the substance is, in fact, the problem of the process, for it is obvious that in a damp climate like Skye, the diatomite does not lose its moisture quickly. The problems which began after the construction of the 1950s road were further highlighted and compounded six years later. A new factory was built at Uig (the site where the Cal Mac offices are now situated), far from the mining site at Loch Cuithir, and it may be said that this move was the ruining of the entire diatomite industry upon Skye. As diatomite was no longer dried at Inver Tote it now had to be transported by road, wet, for the much-needed drying process to Uig, 23 miles away. A vehicle may have left Loch Cuithir carrying five tonnes of Diatomite, yet only producing one tonne of the finished product after drying had taken place – a finished product which was also not as pure as it ought to be for the specialised work it had to do in various products. A lot of money was wasted on travelling, and within the factory itself, inefficiency was also present, with machinery often breaking down due to the damp state of the diatomite. Outside the

Beta version

factory, the scenic communities of Trotternish also began to suffer. When the factory was working, it poured out a fine white dust which covered every house in the area. Grass became chalky in colour and after dry spells in the weather, the road-sides from Staffin to Uig would turn white with diatomite – Uig was constantly under a cloud of dust. With complaints of insubstantial profits and bad management, the factory was finally closed to production for the last time in 1960. Yet, although the diatomite mining industry on Skye came to an abrupt ending, it was still regarded by many locals as a blessing at the time. Following from World War One, the industrial works provided employment for many returning men who could not find work elsewhere in the island. And at peak production, around 1955/56, 50 to 60 men were paid good wages to work at the factory.

Evidence of the former diatomite extraction process occur in a variety of forms: the derelict buildings at Loch Cuithir and Inver Tote, sections of rails from the tramway between Loch Cuithir and Inver Tote, and rusted remnants of wagons used to transport the diatomite (Figure 14-101). Rare photographs of the workers remind us of the importance of diatomite mining to the local population (Figure 14-102).



Figure 14-101: The rusted remnants of a diatomite wagon on the shore at Digg, north of Staffin Bay, Trotternish, Skye.

Pre-submission



Figure 14-102: Diatomite workers at Digg in 1918.

14.16 Geological hazards

The principal geological hazards in the district are rockfalls and landslips along the edges of the Paleocene lava outcrops. Landslipping has long been a problem in parts of northern Skye, where the roads are affected and movement of buildings has occurred as, for example at Flodigarry (Figure 14-103; Figure 14-104; Figure 14-105; Figure 14-106; Figure 14-107; Figure 14-108; Figure 14-109).



Figure 14-103: Landslipped material east of the Trotternish Escarpment at Flodigarry. There is no simple geological logic to the topography, as it comprises rotated and toppled blocks of lava in a totally random manner. Note road sign warning.

Beta version



Figure 14-104: Road sign warning at Flodigarry, Trotternish, Skye.



Figure 14-105: Road damage at Flodigarry, Trotternish, Skye. Repairs are made on an almost annual basis due to ongoing minor movements within the landslipped material as it migrates eastwards towards the coast.

Preview version



Figure 14-106: Landslipped material on the coast at Dunans, south of Flodigarry, Trotternish, Skye. The material comprises rotated and toppled fragments of lava is a totally random manner. Note abandoned building and disrupted line of fence.

These movements are but the latest manifestation of landslipping which has occurred in this area, on Raasay, and elsewhere, since the Late Devensian glaciation. Rockfalls are a particular problem along the edges of the basalt scarps, especially after frost and rain. On Eigg, a house was demolished at Cleadale and there are extensive, recent falls on the coast north of Kildonan.

Beta version



Figure 14-107: Insipient failures within the Druim an Fhuarain Sandstone Member between Creag na Bruaich and Druim an Aonaich on the east coast of Raasay. View towards the south from Brochel.

Beta



Figure 14-108: Detail of major NW-SE -trending fissure within the Beinn na Leac landslip, Raasay. Fissure depth is in excess of 20 m.



Figure 14-109: Detail of major NW-SE -trending fissure within the Beinn na Leac landslip, Raasay.

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M BGS Geological Maps

Arran Special sheet (S) (1:50K)	1987
Sheet 43S, Ross of Mull (S & D) (1:50K)	1999
Sheet 43N Staffa (S & D) (1:50K)	1996
Sheet 44W East Mull (S) (1:50K)	1992
Sheet 51E/52W North Mull & Ardnamurchan (1:50K)	2013
Sheet 60 (S & D) Rum	1994
Sheet 70 Minginish (S & D) (1:50K)	2000
Sheet 71W Broadford (S & D) (1:50K)	2005
Sheet 80W Dunvegan (B & D) (1:50K)	2006
Sheet 80E Portree (1:50K)	2007
Sheet 81W (B & D) Raasay	2006
Sheet 90 Staffin (B & S)	2006
Ardnamurchan Central Complex (B & S) (1: 25K)	2009
Skye Central Complex (S)	2005

S: solid/bedrock; **D:** drift/superficial

Beta version

Back page: Am Bàsteir, northern Cuillin, and Ruadh Stac, Glen Sligachan, Skye.

